AN *EX ANTE* ASSESSMENT OF THE FARM-LEVEL IMPACTS OF FURTHER DEVELOPING SUGARCANE BIOREFINERIES IN THE SOUTH AFRICAN CONTEXT

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ABSTRACT

The gross sugar production in South Africa (SA) tends to exceed the quantity demanded locally. Surplus sugar is sold in the global market at prices that are typically below the cost of sugar production in SA. This amongst other factors has threatened the long-term sustainability for sugarcane production and the industry is seeking for solutions. Expanding the product portfolio is one method and the South African Sugarcane Value Chain Master Plan to 2030 (which was signed in 2020) could aid the process as it has a special focus on feasible and attractive sugarcane-based biorefinery products opportunities, both locally and internationally. A biorefinery scenario challenges the current cane payment system which does not explicitly include payment for fibre, non-sucrose and other fermentable sugars in the event that these become necessary feedstock for biorefineries. In addition, the total proceeds shared between growers and millers are only for local and export sugar and molasses sales, after deduction of the industry's administration costs. This needs careful reconsideration once sugarcane bio-based biorefinery products form part of the product portfolio.

The main objective of this study was to conduct an *ex ante* analysis of the impact of sugarcane biorefinery establishment on farm-level and mill biorefinery investment decisions. A literature review including but not limited to a description of the division of proceeds and the cane payment system in South Africa and other countries involved in sugarcane biorefining as well as an outline of *ex ante* assessment studies in biorefining, was conducted. Literature findings showed that, despite increased feasibility studies in biorefining, studies that link product price interactions, demand and supply of sugarcane and its by-products in South Africa to the farm and mill level impacts of further developing sugarcane biorefineries are lacking. Additionally, the review demonstrates that there are strong economies of size in biorefinery investments and the economic viability of a biorefinery depends on availability of sufficient reasonably priced feedstock delivered to the mill, or providing incentives to growers to supply the biorefinery with sufficient feedstock. Cane payment systems and division of proceeds scenarios were also identified as influencing the biorefinery investment and grower decisions.

Although there are many biorefinery products that can be produced from sugarcane, a limited sub-set of these were considered in this study to demonstrate the concept of further developing sugarcane biorefineries in South Africa. The selection of biorefinery products was, in part, informed by data availability. In particular, technoeconomic and feasibility studies carried out in South Africa informed the choice of which biorefinery products to include in this study.

Lysine from syrup, bio-ethanol from clear juice and bio-methanol as well as electricity which both could be produced from bagasse were the biorefinery products that were assessed in this study.

A partial equilibrium analysis was conducted by compiling and merging three mathematical linear programming representative farm models of a ‘typical’ sugarcane farm for the Eston Cane Supply area, as well as a linear programming model of a representative mill with options to invest in the production of various products (referred to as the biorefinery appended to the mill (BAM) throughout the study). The three farm representative models were constructed with the inclusion of a high fibre variety of cane, energy cane. Demand for molasses, sucrose and sugarcane fibre by the biorefinery appended to the sugar mill was derived from the domestic and export market demands for methanol, ethanol, lysine and co-generation of electricity.

The model was verified using the white-box validation method which involves establishing whether model components accurately represent real world components through inspecting output reports. It was then optimised using a scenario which maximises the total revenue for the partnership of Eston cane growers and the miller for the purposes of division of proceeds. Sensitivity analyses for the different biorefinery product pricing scenarios show that with the current status quo in the SA sugar industry, there is no motivation for the growers to adopt energy cane and the millers to produce any biorefinery products. Moreover, a pseudo-supply curve for the Eston Central region show that without energy cane a price of R1 500 per ton of bagasse over and above payment for sucrose and molasses increases the quantity of fibre supplied by less than 5%. By contrast, in a scenario with energy cane, a price of an average of R445 per ton of bagasse gives rise to a 60% increase in the quantity of fibre supplied. Other notable observations as the fibre price increases include, planting more land under cane as macadamia production declines and an evident shift in sugarcane cultivar selection. There is a direct relationship between fibre supplied by the growers and bagasse produced in the mill in this study.

Market prices for each of the biorefinery products had to be inflated for biorefinery production to begin. At market prices of R12 000, R20 000, R40 000 per ton the mill produces 18 000, 45 000 and 65 000 tons of methanol, ethanol and lysine respectively. Other mill decisions that were adjusted as bagasse prices altered are a switch to the use of a more efficient boiler at a bagasse price of R140. This results in the availability of over 20 000 Megawatt hours (MWh) of surplus electricity annually for sale to the national grid at a price of R344/ MWh (an average price based on the highest and lowest indexed tariffs for bioenergy produced in the Renewable Energy IPP Procurement Programme (REIPPPP)). The optimal solution indicates that the greatest revenue is realised in a scenario that includes lysine, electricity, sugar and molasses with all the sugar produced in all scenarios sold locally. Currently in SA, some sugar is exported and the biorefinery product market prices are below R10 000 per ton except lysine which sells at approximately R20 000 per ton. Cogeneration of electricity for sale to the national grid seems to be the likely viable option as it does not involve huge investment costs and also makes use of bagasse which has currently no other use in the mill except burning it for fuel.

Viability of a sugarcane biorefinery is dependent on a number of factors that include feedstock supply and the right biorefinery product market prices which make biorefinery production feasible. In this study, for the products considered, it is clear that diversification is possible only when market prices are much higher than the prevailing prices. This suggests that biorefinery establishment will require some sort of government protection for example subsidies to ensure feasibility of production for the products used in this study. Maximisation of total proceeds requires creation of the right price incentives so that the growers supply the optimal quantities and cultivars of cane to the mill. This has implications for the pricing of cane and the final division of proceeds from sugarcane production, milling and bio-refinery operations. While it is possible to resuscitate the industry, establishing sugarcane biorefineries requires systems thinking that calls for stakeholders to look at the whole supply chain in totality as the decisions of one affect the other.

PREFACE

I Wadzanai Penlope Mafunga. declare that

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

ii) This thesis has not been submitted for any degree or examination at any other university.

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Signed: [redacted] Date: 27/06/2022

As the candidate's supervisor, I have approved this thesis for submission.

Signed: [redacted] Date: 20 July 2022

S. R.D Ferrer

As the candidate's co-supervisor, I have approved this thesis for submission.

Signed: [redacted] Date: 28 June 2022

A. Stark

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DEDICATION

This thesis is dedicated to the Mafunga family. Knowing that I am the first to break new ground and pursue a Doctorate is such an honour.

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PUBLICATIONS DECLARATION

Details of contribution to publications and conference presentations that form part and /or include research presented in this thesis:

Manuscript 1- Chapter 4 of thesis

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Three conference papers (one short non-reviewed (2017) and two full peer reviewed papers presented at the South African Sugar Technologists' Association August 2019

- **Mafunga WP**, Ferrer S and Stark A. 2017. The development of a partial equilibrium economic model of the South African sugar industry in a biorefinery scenario. *Proceedings of the South African Sugar Technologists' Association,* Mount Edgecombe, Durban, South Africa 90: 406-410.

- **Mafunga WP**, Ferrer S, Botha P and Stark A. 2019a. Adoption and performance of cane cultivars in three regions of the Eston cane supply area. *Proceedings of the South African Sugar Technologists' Association,* Mount Edgecombe, Durban, South Africa 92: 86-97.

  This paper received two awards the **KYNOCH AWARD AND SASTA STUDENT PRIZE: AGRICULTURE*:***

- **Mafunga WP**, Ferrer S, and Stark A. 2019b. The sensitivity of growers' production decisions to changes in the bagasse price for the Eston Central region. *Proceedings of the South African Sugar Technologists' Association,* Mount Edgecombe, Durban, South Africa 92: 123-138.

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ABBREVIATIONS

AUD	Australian Dollars
BAM	Biorefinery Appended to the Mill
BFAP	Bureau for Food and Agricultural Policy
BFP	Biofuels Feedstock Protocol
CABRI	Collaborative Africa Budget Reform Initiative
CCS	Commercial Cane Sugar
CGE	General Equilibrium
CTS	Cane Testing Services
DAFF	Department of Agriculture Forestry and Fisheries
DOP	Division of Proceeds
GDP	Gross Domestic Product
HPL	Health Promotion Levy
IRENA	International Renewable Energy Agency
IRR	Internal Rate of Return
LP	Linear programming
MOTAD	Minimisation of Total Absolute Deviations
MSS	Mauritius Sugar Syndicate
MT	Metric tons
NAMC	National Agricultural Marketing Council
NPG	New Product Greenhouse toolbox
NPV	Net Present Value
PE	Partial Equilibrium
RHS	Right Hand Side
RRV	Relative Recoverable Value
RV	Recoverable Value
SA	South Africa
SACGA	South African Cane Growers' Association
SASA	South African Sugar Association
SASRI	South African Sugarcane Research Institute
S-BEAT	Sugarcane Biorefinery Economic Analysis Toolbox
TEA	Technoeconomic analysis

1. INTRODUCTION

1.1 Background

An increased wave of interest has been noted amongst industries, policy makers and development specialists to transition countries from fossil-based economies to bio-based economies (Staffas *et al*., 2013). This, according to de Jong *et al.* (2012), Amigun *et al*. (2011) and Chen *et al*. (2011) has been prompted by high and fluctuating crude oil prices, fossil resource depletion, local and global environmental impacts of fossil resource consumption such as climate change, opportunities for job creation, new research and technological advances, economic development and the need to increase the access to energy. Bio-based economies use biological resources (from the land and sea) to grow and produce feed, food, renewable materials and energy eco-efficiently while simultaneously reducing the environmental burden and developing disadvantaged areas (coastal and rural areas) (Primer, 2001). This type of economy does not include one segment of the economy but encompasses the chemical industry, forestry, agriculture, food, fisheries and biotechnology sectors, all interacting together towards one goal (Patermann and Aguilar, 2018; Schmidt *et al*., 2012).

Several bioeconomy-related industrial and policy initiatives have been developed in a number of countries in recent years. According to the German Bioeconomy Council (2015b), 49 countries have published bioeconomy related policy strategies with 15 (e.g. Germany, Australia, United States of America, Finland) actually developing the strategies. Although different states have their own priority areas (e.g. agriculture, biotechnology, health, food and energy) and varied approaches to promote bioeconomies, most strategies center on production and use of biological resources to manufacture high-value based products through biorefineries (German Bioeconomy Council, 2015b; Staffas *et al*., 2013). Biorefineries refer to the sustainable processing of different types of biomass (e.g. energy crops, organic residues, aquatic biomass etc.) into bio-based products such as chemicals, fuels, energy, materials and feed (Gheewala *et al.*, 2011; King 2010). They have been identified as fundamental to the support of bio-based economies in various industrial initiatives for different countries (German Bioeconomy Council; 2015b; de Jong and Jungmeier, 2015; de Jong *et al.*, 2012; Demirbas *et al*., 2011).

The biorefinery concept is analogous to the petroleum refinery that also produces fuels and chemicals; the main difference being the source of raw material used in the refining process.

The main aim of a biorefinery is to enhance resource use and reduce wastes, with the objective of maximizing profitability and benefits. Potential biomass sources include wood, agricultural crops (sugarcane, maize, wheat, cassava, soybean, sunflower, avocado, jatropha, switchgrass, grains amongst others), aquatic biomass (seaweeds and algae), agricultural residues (straw, beet leaves, potato peelings, maize stover etc.), as well as household and industry residues (biodegradable municipal waste, sewage, sludge, animal fat and manure) (de Jong and Jungmeier, 2015; Petrie, 2014; Waclawovsky *et al*., 2010). In the United States of America (U.S.A), Brazil, China, Australia and South-East Asia biomass such as maize, sugarcane, sugar beet, cassava, oil palm and potatoes is used in biorefineries (Renó, *et al*., 2014). In some European countries and Japan, biorefineries serve the two-fold role of refuse disposal due to insufficient garbage landfill space. Food wastes, animal wastes, lumber wastes and waste paper provide the raw material for fermentation and energy (Renó *et al*., 2014).

South Africa (SA) launched the South African Bioeconomy Strategy in 2013, which identified the agricultural sector as the one with the highest economic impact. The SA Bioeconomy Strategy states that there is a need to explore the revitalisation of mature industries such as the sugar and wood/forestry industries in order to achieve "eco-efficiency and innovation in a low-carbon future" (Department of Science and Technology, 2013, p.32). In the Industrial Sector Strategy, it is stated that South Africa will need to progressively source second generation biofuels, in particular by converting agricultural residues (Department of Minerals and Energy Affairs, 2007). Recently, in February 2020, publications of the South African Biofuels Regulatory Framework as well as the National Biofuels Feedstock Protocol (BFP) were released by the Department of Mineral Resources and Energy in support of a bioeconomy (Department of Mineral Resources and Energy, 2020). Five major aspects were highlighted in the Biofuels Regulatory Framework including mandatory blending regulations, Feedstock Protocol, cost recovery mechanism for blending biofuels, selection criteria for biofuel projects requiring a subsidy and a Biofuels Subsidy Mechanism. The Biofuels feedstock protocol is meant to control the agricultural production of biofuels thus ensuring sustainable production and mitigating the risk of food insecurity. Grain sorghum, sugarcane and soybeans are among the feedstocks that South Africa is considering for biofuel production.

Presently, in South Africa, the existing sugarcane mills are in essence biorefineries producing sugar, molasses, bagasse and residues that can be either used as feed or fertiliser. The South African sugar industry consists of 14 sugar mills with Tongaat Hulett Sugar Ltd and Illovo Sugar Ltd owning four mills each. RCL Foods Sugar & Milling (Pty) Ltd owns three mills while UCL Company Ltd, Gledhow Sugar Company (pty) Ltd and Umfolozi Sugar Mill (pty) Ltd own one mill each. Only four mills produce their own refined sugar which is exported (SASA, 2020). The gross sugar production in the past years has exceeded the quantity demanded locally (see Table 1-1).

Table 1-1 The total quantities of sugar produced, local market demand and export market

Year **Quantity**	**2014/15**	**2015/16**	**2016/17**	**2017/18**	**2018/19**	**2019/20**
Gross sugar Production (tons)	2 115 463	1 627 395	1 553 229	1 995 072	2 193 321	2 227 248
Local market Demand (tons)	1 649 056	1 573 504	1 534 741	1 190 281	1 140 990	1 249 476
Export Market (tons)	458 617	46 826	4 998	795 434	1 042 831	967 579

(SACGA, 2020)

This has resulted in surplus sugar being sold in the global market at very low sugar prices that are far below the cost of sugar production in South Africa. The Biofuels feedstock protocol highlights that the sugarcane equivalent of additional sugar could be diverted to production of biofuels (Department of Mineral Resources and Energy, 2020). A major milestone has also been made through signing of the South African Sugarcane Value Chain Master Plan to 2030 in November 2020 (Anon, 2020). The Master Plan is a result of extensive consultation and engagement amongst sugar industry stakeholders including cane growers, millers, South African Sugar Association (SASA), South African government, retailers, wholesalers and industrial users. The Master Plan vision is to achieve *"a diversified and globally competitive, sustainable and transformed sugarcane-based value chain that actively contributes to South Africa's conomic and social development, creating prosperity for stakeholders in the sugarcane value chain, the wider bioeconomy, society and the environment", (*Anon, 2020, p.11). Seven task teams have been put in place to provide transitional support and ensure realisation of this vision. One such team is responsible for the sugarcane-based value-chain diversification strategy. It aims to research on feasible and attractive sugarcane-based biorefinery products opportunities locally and internationally, with detailed recommendations on findings. In addition, the task team will also provide detailed recommendations in line with the current sugar industry structure which may include amendments or replacement of the Sugar Industry Agreement (SIA) and the Act 9 of 1978 (hereafter referred to as the Sugar Act) (Anon, 2020).

Considering that sugarcane can be a feedstock for the production of multiple biorefinery products, there is on-going research regarding improvement of the plant for that purpose. The significant and positive contribution of sugarcane to bioenergy (e.g. electricity, bio-ethanol) could be further enhanced with "*energy cane*", which is a hybrid of wild and commercial sugar cane (IRENA, 2019; Matsuoka *et al*., 2014; Kim and Day, 2011). Apart from a much higher yield per hectare of cane harvested, the fibre content of energy cane may be as much as double that of sugar cane and this may have environmental and economic advantages (Carvalho-Netto *et al*., 2014). The SA sugar industry has been historically known to produce sugarcane primarily for sugar production with other products (bagasse and molasses) simply viewed as by-products with low value. As such, the sucrose content is the most important attribute of sugarcane and the type of cane payment system in place creates the needed incentives for upgrading the sucrose content of the sugarcane delivered to the mill.

Problem statement

Further developing SA sugar mills into fully fledged biorefineries (through product expansion), as is suggested by the South African Department of Science and Innovation, makes all bagasse, and fermentable sugars (sucrose and non-sucrose) potential feedstock for the production of various biorefinery products (Naidoo *et al*., 2019a, b; Brent, 2014). This approach, however, poses a challenge to the SA sugar industry: The partnership existing between growers and millers of sugarcane is governed by regulations stating that only the total sales from the export market and domestic market for molasses and sugar should be included in the SA division of proceeds (NAMC, 2013; Moor and Wynne, 2001). Moreover, rules governing the division of proceeds would need to be altered to cater for these additional biorefinery products, ultimately altering the Sugar Industry Agreement (BFAP, 2015; Brent, 2014). The Division of Proceeds (DOP) is the revenue distribution between millers and growers from sugar sales and some cane by-products as well (Todd *et al*., 2004). The current division of proceeds hence assumes an industry that primarily extracts sugar and molasses from sugarcane, any additional products are not accounted for. The existing payment system may need restructuring to accommodate the value of fibre and non-sucrose since at present, growers are effectively penalised for both when delivered in excessive quantities. A new cane payment system needs to drive the correct incentives as well as reward efficiencies and investments in the production processes of additional biorefinery products (BFAP, 2014). Braude and Montmasson-Clair (2019) note that the SA sugar industry has recognised the need to look into the payment system and are currently working on it. The South African Sugarcane Value Chain Master Plan to 2030 and the Biofuels

Regulatory framework are in support of diversification of the sugar industry and task teams are in place to drive this agenda (Anon, 2020; Department of Mineral Resources and Energy, 2020).

Using the biorefinery concept, other attributes apart from sucrose (e.g. other fermentable sugars and fibre) will be essential to consider in the sugarcane plant and this can potentially influence the choice of sugarcane varieties and harvesting methods employed at farm-level. Consequently, consideration of the farm implications of establishing fully fledged biorefineries is critical because this new outlook may possibly influence the farmers' sugarcane production and millers' investment decisions.

1.2 Significance of study

While biorefinery development opens important opportunities for several countries, the economic, environmental and social sustainability aspects need to be carefully considered (de Jong and Jungmeier, 2015). The evolution and the increasing significance of biorefineries calls for new organisational and economic knowledge about the biorefinery concept and its application. Researchers in turn will need to conduct studies that include scenario building as well as analyses of economic, environmental and social impacts along the whole value chain (systems thinking) (Sauvee, 2016). One way of achieving this could be through *ex ante* evaluations or assessments to inform decision making.

UNCTAD (2016) states that an *ex ante* evaluation makes use of data including hypothetical information to estimate the likely outcome of possible future scenarios (future events and conditions) in order to predict the effect of a policy (programme or project) before its implementation. The objective of an *ex ante* assessment is to provide decision makers with information that assists them in evaluating and making a choice in the face of many project alternatives. *Ex ante* assessments enable identification of an optimal design of a program/ policy with desired impacts at the lowest cost or maximum impact for a set cost. This would help evade the high costs associated with implementing programs that will prove ineffective in future. Additionally, *ex ante* evaluations provide evidence on expected and unintended impacts of a program/policy which could assist with ex-post evaluations or selecting accompanying measures when implementing the policy. Vidueira (2014) states that *ex ante* assessments can be termed a 'what if analysis' since they deal with events that may (or may not) occur in the future. Moreover, the analysis can be used to study how the impacts would differ if some parameters of a policy/project are altered (Todd and Wolpin 2008).

Ex ante analysis can take a descriptive or econometric approach depending on the availability of data and resources. A descriptive approach is based on existing statistics providing initial approximations and thus lacks information on the estimated expected impacts (UNCTAD, 2016). Econometric evaluations include estimation with computable general equilibrium models dependent on data from varied sectors of the economy or a microeconomic model, using household, individual or firm level data limited to a specific segment of the economy. This approach enables policymakers to identify fundamental relationships between policy modifications and a given outcome (UNCTAD, 2016).

This study conducts an *ex ante* analysis of the farm-level impacts of further developing sugarcane biorefineries in the South African context using a partial equilibrium model. Sensitivity analysis for different cane payments system scenarios is carried out and the likely outcome of millers' biorefinery investment decisions and the on-farm implications thereof for sugarcane production on representative farms will be identified. Recent biorefinery research has put much emphasis on the environmental impacts, conversion technologies and processes within a biorefinery (Jain *et al*., 2016; Pereira *et al*., 2015; Wang *et al*., 2014; Wanderely *et al*., 2013). Studies have focussed on various crops including corn (maize), sugarcane, wheat, switchgrass, microalgae and sweet sorghum (Wang *et al*., 2014; Quintero *et al*., 2012; Richardson *et al*., 2007; Rajagopalan *et al*., 2005). In the sugarcane industry, several biorefinery techno-economic analyses (TEA) investigating the economic feasibility of technologies and bio-based product combinations have been carried out (Moncada *et al*., 2013; Quintero *et al*., 2012; Dias *et al*., 2009). In South Africa, Gorgens *et al*. (2015) analysed the economic viability of sugarcane annexed biorefinery plants using total investment, variable and production cost estimations and other economic parameters (e.g. Net present value (NPV), Internal Rate of Return (IRR)) based on process simulations for six biorefinery scenarios. Farzad *et al*. (2017) carried out a techno-economic evaluation to model different routes for converting sugarcane bagasse and trash to specific biofuel or biochemicals e.g. butanol, methanol, ethanol and lactic acid. The Sugarcane Technology Enabling Programme for Bioenergy (STEP-Bio), a partnership between the Department of Science and Technology's Sector Innovation Fund and the South African sugarcane processing industry was a key biorefinery programme conducted for a period of three years (2015 to 2019). One of the programme subprojects involved development of techno-economic models aimed at identifying future opportunities targeted towards improving sugarcane biorefinery viability (SMRI, 2020). Guest *et al*. (2019) and Starzak and Davis, (2017) modelled a 'generic' South

African sugar mill to lay the foundation for biorefinery processes modelling. Guest *et al*. (2019) analysed the effect of diverting clear juice portions to a biorefinery on the rest of the mill.

These studies are based on mass and energy balances followed by various optimization processes that account for cost, size, uncertainty, location and feedstock availability. Most of these reviews disregard the influence of supply and demand issues and the impact of a new production process on resource availability and prices. These aspects should be adequately accounted for via a complementary economic market model. In the SA sugar industry, it is necessary to consider sugarcane biorefinery economic sustainability with respect to supply and demand of sugarcane when additional downstream products are introduced into the sugarcane supply chain under different DOP scenarios. Apart from sugar production, selected biorefinery products in this study include lysine, methanol, ethanol and sale of surplus electricity. Lysine and ethanol will use syrup and clear juice as a raw material while bagasse is the main raw material for methanol and electricity generation. The demand for sugarcane is therefore translated into the demand for the sucrose and bagasse by the mill as these will be the main raw materials for biorefinery production in this study.

1.3 Research objectives

The main objective of this study was to conduct an *ex ante* analysis of the farm-level impacts of further developing sugarcane biorefineries in the South African context using a partial equilibrium model. This facilitated the establishment of the likely outcome of millers' biorefinery investment decisions, the on-farm implications thereof for sugarcane production on representative farms as well as implications for the division of proceeds.

The specific objectives of the study are to:

i. To characterise adoption of sugarcane varieties, cane and recoverable value yield performance, opportunity cost of land in the Eston milling region as well as choice of sugarcane production and harvesting methods.
ii. To model representative farms for the Eston milling region (representing supply of sugarcane while accounting for sugarcane fibre and fermentable sugars) as well as determine the sensitivity of the representative farm models to exogenous price changes of bagasse (which has implications on sugarcane pricing) with and without the inclusion of energy cane.
iii. To describe sugarcane biorefinery mill processes

iv. To construct a representative biorefinery appended to the mill model representing the current sugarcane product portfolio and other selected biorefinery investment options.

v. To combine models from objective iii and iv for the construction of a sugarcane sector partial equilibrium model for the Eston region which will be used to establish the likely outcome of millers' biorefinery investment options and the on-farm implications thereof for sugarcane production on representative farms.

vi. To perform sensitivity analysis on the sector model for different cane payment system scenarios, including scenarios with and without fibre and identify the implications of the different scenarios and biorefinery investments on the division of proceeds.

1.4 Structure of the thesis

Chapter 1: Introduction and background

Background information on the importance of *ex ante* analyses and reasons for transition from fossil-based economies to bio-based economies is given in this chapter. An overview of the current state of the SA sugar industry is made with respect to further developing sugarcane mills into fully fledged biorefineries. This includes all the strategies and progress made thus far towards a bio-based economy. The problem statement, significance of the study and objectives are clearly laid out in this chapter. There is also mention of the specific biorefinery products this study focuses on.

Chapter 2: Literature review

Literature on certain issues relevant to the study is reviewed in this chapter. The first section briefly outlines the challenges currently existing in the SA sugar industry and highlights progress that has been made towards a bioeconomy. The next section is an overview of the sugar market in South Africa and globally. Following is an outline of division of proceeds and the cane payment system in South Africa as well as other countries involved in sugarcane biorefining. An overview of sugarcane biorefinery development globally and in South Africa as well as the energy cane concept are detailed in Section 2.4. Additionally, in this section, the state of the market for biorefinery product choices specific to this study are reviewed. *Ex ante* assessment studies in agriculture and the field of biorefinery are presented in Section 2.5. In Section 2.6, an overview of the use of partial equilibrium modelling in agriculture as well as its relevance in this study is done. Following, is Section 2.7 where farm-level models that have been used in *ex ante* studies together with the methodologies applied are described. Lastly, in Section 2.8, studies that have used linear programming for various optimisation decisions in the manufacturing/operations departments are profiled.

Chapter 3: Research methodology

This chapter begins with a description of the selected study area in detail and explains how data for cane cultivar adoption and sugarcane farming production activities for the Eston region was gathered. In Section 3.2 the method of constructing three representative farm models of the Eston cane supply area is described. A hypothetical cultivar of cane, energy cane, is incorporated in each of the farm models as part of the methodology. A full explanation of the model components, inclusion of risk, model optimisation and validation of the model is explained in detail. In Section 3.3 and Section 3.4 an outline of constraints and activities in the biorefinery appended to the mill (BAM) representative model and how the model is constructed is given. An explanation of market demand data addition to the BAM model for the selected biorefinery products is given in Section 3.5. The methodology for combining the three representative farm models and the BAM model to make a complete sugar sector partial equilibrium model for the Eston cane supply area is outlined in the final section.

Chapter 4: Results and discussion

The results of the study are presented, interpreted and discussed in this chapter.

Chapter 5: Conclusions and Recommendations

The major conclusions of the study are summarised. The implications of the research findings for policy and decision making in the country and the sugar industry are outlined. Recommendations for future work, challenges, limitations and opportunities are identified.

2. LITERATURE REVIEW

Literature on certain issues relevant to the study is reviewed in this chapter. The first section briefly outlines the challenges currently existing in the SA sugar industry and highlights progress that has been made towards a bioeconomy. The next section is an overview of the sugar market in South Africa and globally. Following is an outline of division of proceeds and the cane payment system in South Africa as well as other countries involved in sugarcane biorefining. An overview of sugarcane biorefinery development globally and in South Africa as well as the energy cane concept are detailed in Section 2.4. Additionally, in this section, the state of the market for biorefinery product choices specific to this study are reviewed. *Ex ante* assessment studies in agriculture and biorefining are presented in Section 2.5. In Section 2.6, an overview of the use of partial equilibrium modelling in agriculture as well as its relevance in this study is done. Following, is Section 2.7 where farm-level models that have been used in *ex ante* studies together with the methodologies applied are described. Lastly, in Section 2.8, studies that have used linear programming for various optimisation decisions in the manufacturing/operations departments are profiled.

2.1 The SA sugar industry and current strides towards a bioeconomy

An estimated 110 countries contribute to the world's sugar supply either through sugarcane or beet production (International Sugar Organisation, 2021; Mandegari *et al.*, 2017a). A large proportion of world sugar production (80%) is from sugarcane with India, Brazil, Thailand, China, the United States (US), Mexico, Russia, Pakistan, France, Australia ranking among the top 10 producers of sugarcane (International Sugar Organisation, 2021). South Africa's sugar industry is positioned among the top 22 sugar producers and in 2018 the country was ranked as the 6th largest net exporter of raw sugar (International Sugar Organisation, 2021; SASA, 2021).

Over the years the industry has encountered financial crisis beginning with a series of droughts in the years 2014 to 2017. The Health Promotion Levy (HPL), implemented in 2018/19 resulted in a reduced demand for sugar which was a huge blow to an industry that already produces more relative to the quantity demanded (SACGA, 2020). Excess sugar is sold on the global market at very low prices that are below the cost of production in SA. In the 2021 season, there was a R2 billion reduction in industry revenue due to duty free sugar imports from Eswatini

(SACGA, 2021a). In August 2018, a higher Dollar Based Reference Price of US$680 eased the influx of deep-sea imports. Other efforts by the South African Cane Growers Association (SACGA) to support the industry include campaigns such as the "home sweet home" launched in 2020 that reached a total of 100 million people. The purpose of the campaign was to inform consumers about the importance of buying sugar produced locally (SACGA, 2021a).

The Sugarcane Value Chain Master Plan to 2030 was signed in November 2020 and is heralded as a step towards sustainability for the industry. The Master plan involves seven task teams namely; South African Custom's Union harmonisation, job retention and mitigation strategy, small-scale growers' masterplan, transformation, crop diversification strategy, sugarcane-based-value-chain diversification strategy and product tax policy aimed at driving the rescue strategy for the industry (SASA, 2020). This study investigates the viability of the sugarcane-based-value-chain diversification strategy specifically through using cane by-products for production of other biorefinery products other than sugar.

Current strides towards a bioeconomy in South Africa

The 2013 South African Bioeconomy Strategy identified the agricultural sector as the one with the highest economic impact. In the 2007 Industrial Sector Strategy, the importance of utilising agricultural residues for second generation biofuel production is emphasised (Department of Minerals and Energy Affairs, 2007). Recently, in February 2020, publications of the South African Biofuels Regulatory Framework as well as the National Biofuels Feedstock Protocol (BFP) were released by the Department of Mineral Resources and Energy in support of a bioeconomy (Department of Mineral Resources and Energy, 2020). This South African Biofuels Regulatory Framework provides a regulatory and policy framework that facilitates implementation of the 2007 Biofuels Industrial Strategy. Five major aspects were highlighted in the Biofuels Regulatory Framework including mandatory blending regulations which create a biofuels demand by obligating petrol and diesel manufacturers to blend a minimum 2% mandatory blending of bio-ethanol into petrol and a minimum 5% mandatory blending of a biofuel into diesel. The Biofuels feedstock protocol is meant to control the agricultural production of biofuels with grain sorghum, sugarcane and soybeans amongst the feedstocks that South Africa is considering for biofuel production (Department of Mineral Resources and Energy, 2020). Second and third generation biofuel production is recognised by the feedstock protocol as a sure way to eliminate the threat of depleting food sources by using them for fuel production (food versus fuel debate) (Department of Mineral Resources and Energy, 2020).

Second (2G) and third generation (3G) biorefineries employ more advanced technologies and utilise lignocellulosic material (from non-food crops such as energy crops, wheat straw and wood) and microorganisms biomass (algae and bacteria) respectively (Satari and Jaiswal, 2021; Bhatia *et al* 2020; Dias *et al*., 2014; Demirbas *et al*., 2011).

2.2 Overview of the sugar market in South Africa and globally

The global sugar market is one of the highly distorted markets mainly due to a number of protectionist policies in many sugar producing countries (Svatoš *et al*., 2013). Low cost producers of the commodity, for example Brazil, play a major role in world sugar price determination due to their market dominance (Rocha 2013; Mitchell, 2004). Therefore, to protect their domestic markets, several government interventions (e.g. tariffs, quotas, price floors, production controls and subsidies) have been put in place by various countries (Sinclair and Countryman, 2019). As a result, the sugar market consists of two different markets, the controlled and freely traded market.

The freely traded raw sugar market has the sugar price determined by the supply and demand market signals with the price benchmarked against the New York Board of Trade Raw Sugar Futures Contract Number 11 (NY11) (Anon, 2006). In the long run, this supply and demand equilibrium generates a world sugar price cycle. The New York Board of Trade trades NY11 on a futures contract, accepting deliveries from approximately 28 sugar manufacturing countries (Anon, 2006). The controlled market is influenced by various government interventions resulting in over production of the commodity with excess sold to the free trading market at low prices (Sinclair and Countryman, 2019; Rumánková and Smutka, 2013; Mitchell, 2004).

South Africa holds membership of two Regional Trade Agreements (RTAs) namely Southern African Customs Union (SACU) and the Southern African Development Community (SADC). Duty free trade exists between South Africa and other SACU member countries (eSwatini, Namibia, Lesotho and Botswana) leading to South Africa taking up 60% of the SACU market share (NAMC, 2011). eSwatini and South Africa are the only sugar cane producers in SACU and in recent years the duty-free trade within the trading bloc has led to a surge in sugar imports from eSwatini as highlighted in Section 2.1.

Although South Africa has competitive production efficiencies, exporting profitably to the world market is a challenge because of depressed world prices. The Covid 19 pandemic led to an increase in global sugar prices between the period May 2020 to February 2021 largely due to weak exchange rates and reduced crop estimates in countries such as India and the EU. Albeit this positive, the export sugar sales in the 2020/21 season were predominantly unprofitable (SACGA, 2021a).

The global market distortions additionally threaten the maintenance of sustainable domestic sugar prices. Presently, the Sugar Act and the Sugar Industry Agreement (SIA) govern SA’s sugar sector with the Department of Trade, Industry and Competition controlling the industry. Existing protection measures include tariff protection, allowance of the establishment of equal export obligations for growers and millers and the Southern African Development Community’s (SADC) Sugar Co-operation Agreement. This demonstrates a heavily regulated industry (NAMC, 2011). The South African Sugar Association (SASA) determines the domestic notional market prices for molasses, raw and refined sugar. This notional price provides a base for calculation of industry proceeds as well as redistribution of proceeds amongst millers and growers (NAMC, 2013; NAMC, 2011).

The following section outlines how the redistribution of proceeds and cane payment is implemented in the South African sugar industry as well as other countries. The review focuses on SA and those countries that have incorporated biorefinery products in the division of proceeds. Both local market sales and export sales are considered in the distribution of proceeds.

2.3 Division of proceeds, sugarcane payment systems in South Africa and other countries involved in sugarcane biorefining

The division of proceeds is the revenue distribution between millers and growers from sugar sales and sometimes cane by-products as well. While industrial proceeds from all sugarcane growing countries emanate from the sale of raw sugar, in some countries, ethanol and/or molasses sales are incorporated in the total industrial revenue. The division of proceeds have been implemented in the South African sugar industry from 1936 (Jordan, 1992). A cane payment system becomes the means via which growers receive their share of proceeds. Depending on the country or region, various revenue sharing agreements are used to distribute the growers share of industrial proceeds (Ravno, 2000). These arrangements depend on various factors including government support policies, level of industry administration and regulation as well as the number of income streams generating the revenue. In South Africa, net industry proceeds are shared between millers and growers at a fixed ratio of 35.6873 and 64.3127% respectively after, the deduction of operational and administration costs (Mafunga *et al*., 2019b; Sugar Industry Agreement, 2000).

2.3.1 The South African sugarcane payment system

The South African payment system transitioned from a sucrose-based payment system which began in the 1926/27 season to the Relative Recoverable Value (RRV) system in the 1999/2000 season (Wynne *et al*. 2009, Peacock and Schorn, 2002; Groom 1999; Robertson and Donaldson, 1998). The sucrose-based payment system rewards cane growers for the ‘pol’ or sucrose in the cane at a fixed price per ton of sucrose while the RRV system pays growers solely for actual molasses and sugar recovered from their cane. Recoverable value (RV) is defined as the value of molasses and sugar recovered from sugarcane delivered by an individual grower. Developed by an industrial committee, the RRV cane payment system is based on the Estimated Recoverable Crystal (ERC) formula by van Hengel (1974) which recognises the impact of non-sucrose and fibre on sugar recovery. An RV formula, (Equation 2.1) is used in the calculation of recoverable value in the RV payment system.

$$RV = S - dN - cF \qquad (2.1)$$

Where:

F - fibre % cane

S - sucrose % cane,

N - non-sucrose % cane,

d - relative value of sucrose which each unit of non-sucrose redirects from sugar production to molasses and

c - loss of sucrose from sugar production per unit of fibre.

According to NAMC (2013), the *d* coefficient is currently set at 0.4 and is calculated monthly based on molasses and sugar price estimates. The *c* coefficient is at 0.02 and is calculated once per year based on a three-season rolling average.

The RRV payment system additionally reduces motivation for growers to harvest cane only when sugar levels are high as there is compensation for growers delivering cane at the start and end of the season. This enables control of deliveries and evens out the seasonal variations in sugar content (Stray *et al*., 2012).

Following the division of proceeds, an RV price, by which farmers are paid per ton of RV produced is calculated using the formula illustrated in Equation 2.2:

$$RVP = \frac{G - L}{T} \qquad (2.2)$$

Where:

RVP - recoverable value price,

G - grower's share of 64%,

L - South African Cane Growers Association Levy (SACGAL) and

T - tons of RV produced.

2.3.2 Implications of biorefinery establishment on cane payment

In a biorefinery scenario, where sugarcane fibre or fermentable sugars becomes feedstock for the production of various biorefinery products, a cane payment system incentivising only sucrose production may deter progress in biorefinery development. Thus, the existing payment system may need restructuring to accommodate the value of non-sucrose and fibre, since currently, there is no explicit payment for delivery of the two.

Considering that the South African sugar industry has conducted discussions around product diversification through biorefinery establishment, an alternative cane payment system is a necessity to drive this agenda. As highlighted previously in Section 2.3.1, the RV payment system incentivises growers to increase the sucrose content in cane while minimising fibre and non-sucrose. In a scenario where value added products can be made from fibre and non-sucrose, income streams from these additional products should be distributed in such a way that growers and millers are rewarded fairly. A new cane payment system needs to drive the correct incentives as well as reward efficiencies and investments in the production processes of additional biorefinery products (BFAP, 2014). The following section looks into how other cane payment systems for countries with annexed biorefineries are set up and the benefits received since implementing biorefinery operations.

Mauritius

Following trade liberalisation, the Mauritius sugar sector has diversified through production of special and refined sugars, electricity, ethanol and fair-trade sugar. In 2017, bagasse electricity contributed 14.8% of the total electricity produced in the country. The country's limited renewable resources and absence of fossil fuel reserves have been a major motivation for the use of biomass specifically bagasse for energy production. In the same year (2017), about 56% of the total sugarcane molasses produced was a feedstock for export hydrous ethanol production, 12% was used for potable alcohol production and the remaining 32% was exported (CABRI, 2019).

Sugar marketing and export for local sugar in Mauritius is coordinated by an independent and private organisation, the Mauritius Sugar Syndicate (MSS). All millers and growers are members of MSS with the administration and management carried out by 22 of the members known as the "Committee" (Mauritius Sugar Syndicate, 2019). Additional services done by MSS include; distribution of proceeds; service assistance to sugar producers, crop financing, planning and logistics, monitoring food safety and quality sugar standards

The Mauritius Government has launched various schemes in the past to support the sugarcane sector. One such scheme was providing an 80% advance payment to sugarcane planters in 2014 to assist with production costs prior to abolishment of the European Union sugar quota by 2017. These funds are administered by the Syndicate via payment of weekly advances on total sugar produced. Payment is made through appointed cooperative societies/middlemen and brokers or directly processed into producers' bank accounts until full settlement of the remaining amount in June/July the succeeding year.

Out of the total sugar produced, 78% is allocated to growers and 22% to millers (Deepchand, 2005). Based on the sucrose content of cane, an ex-syndicate price per ton of sugar is paid to both millers and growers through the formula:

$$SP = (GR - OC - SP)/TP \qquad (2.3)$$

Where:

SP – the ex-Syndicate price

GR - gross receipts

OC - direct operating costs

SP - statutory payments

TP – total production.

The Mauritius Cane Industry Authority measures sugar extraction rates and ensures weighbridges are calibrated correctly. Additional income for the growers also arises from the following:

(a) 100% of the molasses from their cane

(b) 38% share in the revenue (also known as bagasse transfer price fund) obtained from the sale or bagasse use other than powering the sugar factory (12% is for miller-planters and 50% for power producers).

(c) payment by bottlers and distillers for the sale of cane alcohol in the local market;

(d) a contribution from the Sugar Cane Sustainability Fund to mitigate growers' economic risks

(e) reimbursement in case of major shortfall in sugar production

(f) additional compensation with regard to transport costs if distance to the mill exceeds 6.4km, closure of some cane delivery sites and a component of the fair-trade premium acquired by certified co-operatives which the growers belong to (Mauritius Sugar Syndicate, 2019)

Government support is readily available depending on the situation and all payments are catered for through the MSS. The key drivers of economic sustainability in the Mauritius cane industry have anchored on timely continuous development of appropriate strategies and policies followed by coordinated action plans and enhancement of diverse revenue streams mostly from cane biomass (CABRI, 2019; Mauritius Sugar Syndicate, 2019). The setting up of an independent organisation following all developments at international level, consulting and liaising with all industry stakeholders while advising and reporting to the government has been useful in advancing the Mauritius cane industry.

Brazil

Due to the 1970's oil crisis, the Brazilian Alcohol Program (Proalcool) was launched in 1975 by the Brazilian government in order to increase alcohol production for fuel use (Lopes, *et al*., 2016; Coelho *et al*., 2006). Good production management for both ethanol and sugarcane, infrastructure investment and technological achievements have all contributed to the success of the ethanol production program. Brazil has become a world benchmark for sugarcane produced ethanol and supplies 28% of the world's total ethanol production (Bordonal *et al*., 2018). In 2017, 55% of sugar cane was converted into ethanol, 45% into sugar and 6% of the ethanol was exported (Agriculture Strategies, 2018). The need for government support through subsidies or any other form has been minimised as private investments fund alcohol mill construction (Coelho *et al*., 2006).

As highlighted earlier on, Brazil is a major sugar producer and is one of the few countries including the sale of both ethanol and sugar in its cane payment system. The Uniao da Agroindustriea Canavieira de Sa˜o Pauo (UNICA, mills) and the Organizac-a˜o dos Plantadores de Cana do Estado de Sa˜o Paulo (ORPLANA, producers) in 1999 agreed to a non-profit payment system called CONSECANA-SP (Conselho dos Productores de Cana-de-Ac-u´ car, Asucar e A´ lcool do Estado de Sa˜o Paulo-Consecana) aimed to stabilize prices (Hira and de Oliveira, 2009). The payment is a quality-based system incorporating the quality of cane and prices of sugar, hydrous ethanol and anhydrous ethanol. Recoverable sugar is the measure of cane quality quantified in kilograms of the total reducing sugars (TRS). The wet bagasse weight (to represent the fibre in cane) and brix and juice polarisation are measured at delivery. Equation 2.4 below shows the cane payment formula used to pay growers.

$$TRS = 9.6316 * PC + 9.15 * RSS \qquad (2.4)$$

Where:

PC - Pol in cane (apparent sucrose), and

RSS - is reducing sugars in sugarcane (glucose + fructose) (Marques *et al*., 2015)

The TRS price is calculated using a formula that accounts for the price of white sugar in domestic and international markets, the international market price of very high polarity sugar, and the domestic and international market prices of anhydrous and hydrous ethanol. These prices are stipulated by the Centro de Estudos Avancados em Economia Aplicada (CEPEA).

The distribution of revenue for ethanol and sugar differs slightly with growers receiving 59.5% for sugar and 62.1% for ethanol. Partial payments for cane are administered to growers throughout the season with the Conselho dos Produtores de Cana-de-açúcar, Açúcar e Álcool do Estado de São Paulo (The Council of Sugarcane, Sugar, and Ethanol Producers of the State of Sao Paulo (Consecana)) drawing up the basis for payment. For the 2019/20 season a new technical parameter was introduced as part of the criteria for sugarcane payment. Sugarcane growers supplying cane with a higher purity level compared to the average index for sugarcane processed in two weeks were entitled to a premium paid by the mills.

While Brazil is naturally endowed with productive land, strong governmental support has aided in placing Brazil amongst the top world’s sugar and ethanol producers. Government, among other things;

- provides tax incentives e.g. the tax on industrialised products is less for flex-fuel vehicles compared to gasoline powered vehicles
- mandates minimum blending of ethanol into gasoline (Belincanta and Da Silva, 2016)
- national fuel price setting by Petrobras (a state-controlled company)
- the Brazilian government has banned the private purchase of diesel-powered vehicles since the 1970s
- encourages manufacturing of flex-fuel vehicles
- provides interim subsidies during stressful times specifically for Northeast cane (ABSugar, 2019)

Colombia

Colombia’s sugar production occurs all year round allowing the country to meet local demand without supply interruptions. Most of the sugarcane production occurs on 240 000 hectares of land located on the Cauca river valley where six ethanol distilleries and 15 mills are also sited (Dussán *et al*., 2019; USDA, 2019). Presently, the country specializes in the production of ethanol, molasses and sugar with the mills and distilleries located close to each other for efficient and easy access to sugarcane (Dussán *et al*., 2019; USDA, 2019). The ethanol producing mills are energy self-sufficient using bagasse as a fuel and contributing approximately 1% of bagasse electricity to the national grid. Ethanol production begun in 2005 and currently the domestic ethanol demand offsets sugar exports. Sugarcane is devoted to ethanol production limiting any further increase in sugar production (USDA, 2019).

Three cane payment systems exist in the country that are depended on specific grower and miller situations which are:

- when growers are responsible for all cane growing and harvesting costs they are entitled to 50% of the sugar sales by the individual mill to the export and domestic markets. The miller guarantees a return of 58 kg of sugar per ton of delivered cane for an average sugar content of 11.6%
- when processors rent the land, but the land rent is dependent on the campaign result, growers get 25 to 27 kg of the value of sugar sales per ton of harvested cane.
- when processors rent the land at a fixed amount, the land owner is paid a value of between 100 kg and 116 kg of sugar sales per plaza (1 plaza = 0.64 hectares) per month.

The Sugar Price Stabilisation Fund (FEPA) chaired by the Ministry of Agriculture obtains reports on volume of sales to both local and export markets as well as monthly minimum reference prices for sugar from the millers. Only sales of sugar and ethanol are shared between growers and millers, additional revenue from bagasse-based energy sales or molasses are for the miller only. The table below shows the calculation leading to a 50% share that growers receive from ethanol sales.

Table 2-1 Colombia – Growers’ Share in Fuel Ethanol Sales

Description	**Quantity**
Fuel ethanol output from 1 ton of cane	78 litres
Subtract the equivalent of processing costs	12 litres
Subtract ethanol production from received 28 kg of molasses	7 litres
Total	59 litres
Grower’s share (50%)	29.5 litres

There is therefore no average price of cane due to the specifics of revenue sharing for ethanol or sugar sales.

The success of the domestic ethanol industry can partly be traced back to good Colombian government policies and supportive regulatory frameworks. Some of these include financial and tax incentives to stimulate biofuel production and the marketing, regulation of ethanol and biodiesel domestic consumption (Mejía**,** 2011).

Australia

Australia's sugarcane is primarily grown in Queensland (95%) and northern New South Wales (5%). Deregulation of Queensland's sugar industry occurred in 2006 with two major measures including elimination of restrictions on raw sugar marketing for export and allowance of stakeholders to negotiate contractual terms including price issues (Australia Government, 2021). This resulted in Queensland Sugar Limited (QSL) entering into voluntary marketing agreements with most Queensland mills for their exported raw sugar. QSL is thus responsible for over 90% of Australian sugar exports with other mills not contracted to Queensland Sugar Limited marketing their sugar independently. The proceeds from export sales are pooled and distributed to growers and millers after deduction of marketing costs. Although the cane payment in Queensland is based on the sugar price and sugar content of cane only, a number of lessons can be learnt from the way it is administered. The cane payment formula is:

$$Pc = Ps\,x\,(90/100)\,x\,(CCS - 4)/100 + constant \tag{2.5}$$

Where;

Pc - Price of cane Australian dollars (AUD) per tonne paid to growers during the milling season

Ps - Final price of raw sugar in AUD per IPS tonne. IPS – International Polarisation Scale considering futures, premiums and costs,

$90/100$ - An average sugar recovery rate – an industry standard based on 90 tons **of** standard quality sugar recovered for each 100 tonnes of CCS.

CCS - Commercial Cane Sugar, a measure of recoverable cane expressed as a percentage

4 - A one-third share of the CCS – an industry standard based on a one-third to two-thirds ratio split of CCS at 12%, where two-thirds goes to the grower and one-third to the miller Out of 12 CCS units at standard efficiency, the miller is entitled to gain sales from four of the units with the balance given to the grower

$constant$ - Expressed in AUD per tonne of cane – based on a series of adjustments made over time to reflect changed conditions

Individual millers and growers can now independently of each other control their own raw sugar price exposure. As a result, cane payment arrangements have been adjusted accordingly and consequently, millers and growers are able to select who markets the sugar quantity for a specific price exposure, referred to as Grower Economic Interest (GEI) sugar and Mill Economic Interest (MEI) sugar, respectively:

- Grower Economic Interest (GEI) sugar = $Tons\ of\ cane\ x\ 0.009\ x\ (CCS - 4)$.
- Mill Economic Interest (MEI) sugar =$Total\ sugar\ produced - GEI\ sugar$.

In New South Wales, white and raw sugar is mostly directly sold onto the domestic market due to the close proximity of the area to domestic markets via the New South Wales Sugar Milling Co-operative. Commercial Cane Sugar is also the basis for payment with mills paying on a relative CCS scheme. Two weeks after cane delivery, the first payment of approximately 40% of the total value less harvesting costs is made. Following the end of the crush season, 10% of the other payment is done less industry levies. While remaining payments are made every one or two months, the final settlement is made when the final price is determined. Growers who supply trash to the mill are paid separately by the mill.

The important factors to note about the Australian sugar industry are:

- The country has no sugar policy
- The government plays no role in sugar industry trade
- There are no subsidies, duty or tariffs to protect the local industry (tariff protection was eliminated in 1997)
- It is fully unprotected from world sugar market
- The local sugar market is open to imports, import restrictions were removed in 1988 (Breguet, 2012)

Out of the best sugar producing countries, Brazil and Colombia's total proceeds include sugar and ethanol whereas South Africa, Costa Rica, El Salvado, Eswatini, Fiji, and the US have their total revenue arising from sugar and molasses sales. Australia, Thailand, Indonesia, Dominican Republic, Kenya, Mexico and Philippines recognise industrial proceeds from the sale of sugar only. Mauritius, Belize and Reunion Island are the only sugar industries where payment for bagasse is an additional component of the payment system (International Sugar Journal, 2018).

This section of the literature review has focused on a few of the above listed countries due to information availability. While, all reviewed countries have a type of revenue sharing agreement, the products included in revenue sharing can differ. Interestingly, biorefinery products included in the division of proceeds are successfully produced in those countries e.g. electricity generation in Mauritius, bio-ethanol in Brazil and Colombia. The review also demonstrates that there is room for flexibility in establishing a cane payment system depending on the incentives being driven by a specific country's sugar industry. In Colombia for example, there are three types of cane payment systems depending on the miller grower situations. The next section sheds more light on the state of sugarcane biorefinery development both in South Africa and at global level.

2.4 Sugarcane biorefinery development globally and in South Africa

O'Hara *et al.* (2013) confirm that sugarcane biorefineries co-producing bio-products, fuels and green chemicals provide a great opportunity for improving the sustainability and profitability of sugarcane industries globally. This is because a sugarcane biorefinery can potentially integrate various processes including biofuel production, chemical processes (from ethanol and sugar), electricity and heat generation within the same physical space (Vaz, 2017). Different sugarcane biorefinery propositions have been made. The first and mostly used one is the first generation sugarcane biorefinery that produces sugar, ethanol and electricity (Dias *et al.*, 2013).

In general, first generation biorefineries use conventional technology processes that make use of starch, sugar, animal fats and vegetable oils. Approximately 70% of the sugarcane mills in Brazil are first generation annexed plants producing both sugar and ethanol for over 30 years (Junqueira *et al*., 2017; Losordo *et al*., 2016; Mariano *et al*., 2013a, b; Cavalett *et al*., 2011). Fifty five percent of cane is transformed to ethanol yielding about 68 litres per metric ton of sugarcane (Bezerra and Ragauskas, 2016). The most common scenario in Brazil's annexed plants diverts half of the sugarcane juice plus molasses for bio-ethanol production and the remaining half for sugar production. This flexibility to vary sugar and ethanol production quantities depending on market demand has been one of the reasons for a successful bio-ethanol production industry in Brazil. The major challenge, however, is the extent of operation flexibility in an installed plant, which is limited to the capacity of the facility and other existing design restrictions (Cavalett *et al*., 2011). In Australia, while there are a number of biorefineries using wheat and sorghum, there is the Sarina plant that produces ethanol by fermentation of molasses with a production capacity of 60ML (Country report Australia, 2015). Other countries, including India, Guatemala, El Salvador and Colombia also make use of first-generation processes with sugarcane as the primary feedstock source for ethanol production.

In Africa, due to the maturity of first generation bio-ethanol technology, a number of countries such as Zimbabwe, Malawi, Tanzania, Mozambique, Kenya, Zambia, Egypt, Angola, Swaziland, Uganda and Ethiopia produce the commodity from sugar molasses (Amigun *et al.*, 2011). Zimbabwe and Malawi have implemented mandatory blending of bio-ethanol with petrol of up to 20% (Stafford *et al.*, 2019). Green Fuel company and Tongaat Hulett companies in Zimbabwe are the only bio-ethanol producers in the country. The Chisumbanje Green Fuel bio-ethanol plant in Zimbabwe has an installed capacity of 120 million litres of bio-ethanol per annum and produces 18MW of electricity (Green Fuel, 2021; Pindiriri, 2016). Ethanol production from sugar molasses in Malawi is done at Dwangwa Estate where 10-12ML are produced annually. Africa, however, contributes less than one percent ethanol to the global market mainly because of poor transport infrastructure limiting export as well as low domestic demand (Stafford *et al.*, 2019).

Zambia and Mozambique have biofuels policy regulations which are yet to be implemented (Jha and Schmidt, 2021). Presently, there are no commercial biodiesel plants in Africa as majority of African countries are in the initial stages of biodiesel development. The biodiesel plant in Lilongwe Malawi produces 5 000L of biodiesel from jatropha oil seed (Jha and Schmidt, 2021).

Sugarcane bagasse has also received much attention as a potential feedstock in second generation (2G) biorefineries, especially for ethanol production (Losordo *et al.*, 2016; Restrepo-Serna *et al.*, 2018). Increased ethanol demand due to the rise in biofuel use and its application as a precursor to many other chemicals worldwide has led to the development of 2G ethanol (ethanol production using lignocellulosic feedstock) (Junqueira *et al*, 2016). Second generation ethanol production is now at commercial level although a number of scale up and technological constraints exist (Silveira *et al*., 2018). A few plants have been installed globally including two plants at Granbio (Alagoas) and Raízen (São Paulo) in Brazil with bagasse as a feedstock. The two commenced operation in 2014/15 with Granbio's installed capacity at 80 million litres per year and Raízen's at 40 million litres (Junqueira *et al*, 2017; Stafford *et al*. 2019). Recently, Granbio received a Roundtable on Sustainable Biomaterials (RSB) certificate which validates that its 2G ethanol in comparison with its fossil equivalent has a very low carbon footprint that is lower by 91% (RSB, 2021)

Already in 1987, Paturau (1987) estimated that there could be more than 150 value-added products from sugarcane milling by-products (bagasse, molasses, filter mud) in the future. Consequently, there are many proposed configurations for sugar mills, including integrated sugar mills with ethanol, bio-ethyelene, bio-butanol and methanol (Naidoo *et al.*, 2019a, b; Pereira *et al.*, 2015; Renó *et al.*, 2014). In Brazil and India, bio-ethylene plants, with bio-ethanol as feedstock are in operation accounting for about 0.3% of the world ethylene capacity (ETSAP and IRENA, 2013). Bio-butanol has superior fuel properties compared to bio-ethanol and can be used as a chemical for many other applications (Pereira *et al.*, 2014). HC Sucroquímica in Brazil is an example of a sugarcane biorefinery producing butanol (Mariano *et al*., 2013a, b).

South Africa’s sugarcane mills are first generation biorefineries mainly producing sugar, molasses, bagasse and other residues. A few sugarcane biorefinery examples already exist in SA: the Sezela mill converts bagasse to furfural and other co-products, while bagasse from the Gledhow sugar mill is processed by the SAPPI Stanger paper mill to paper and tissue wadding. NCP Alcohols is an example of a plant producing bio-ethanol from sugarcane molasses in South Africa. The company produces different bio-ethanol grades which are used as raw materials in the manufacture of alcoholic beverages, pharmaceuticals, homecare products, cosmetics, essences, industrial products, toiletries, and are an intermediate in the manufacture of chemicals such as acetic acid, acrylates and esters (Alconcp, 2021). Table 2-2 indicates the various product portfolios for the six sugarcane milling companies in South Africa.

Table 2-2 Product profile of the six South African sugar milling companies

South African Sugar Milling Companies: Operations and Products	
Tongaat Hulett Sugar Ltd	– Retail white and brown sugar – Industrial sugars and sweeteners – Catering sugars and non-nutritive sugars – Electricity generation from bagasse for mill operations – Animal feed (Voermol Feeds)
RCL Foods Sugar & Milling (Pty)	– 3 mills, 2 of the mills have refineries – A packaging plant – Sugar estates – Animal feed division – Cane and sugar transport
Gledhow Sugar Company (Pty) Ltd.	– Refined white sugar – Bagasse is used for boiler fuel for operations and is sent to Sappi – Molasses is sent to a distillery
Umfolozi Sugar Mill (Pty) Ltd	– Brown sugar – Electricity from bagasse for operations – Molasses is sent to NCP alcohols
UCL Company (Pty) Ltd	– VHP brown sugar and molasses – Wattle extract – Electricity from bagasse for operations – Operates a sugar mill, sawmill, wattle extract factory, a trading division, four farming estates, and a cane seed nursery
Illovo Sugar (Pty) Ltd	– Industrial sugar – Refined and brown pre-packed sugar – Bulk raw sugar for refining, molasses, and syrup – Speciality sugars – Electricity is produced from bagasse to power operations – Sezela downstream: o Furfural, furfural alcohol, diacetyl, 2,3-pentanedione, natural methanol and agricultural nematicides – Merebank, Glendale and Tanzania ethanol distilleries: o Ethanol (potable extra neutral alcohol, 96%), anhydrous alcohol (99.9%), rectified extra neutral alcohol (96%), industrial alcohol (95%) and lactulose (Merebank distillery) – Ubombo Mill in Eswatini: o Electricity powers the mill operations and power is exported to the Eswatini grid according to an agreement with the Eswatini Electricity Company

(Naidoo, 2020)

As shown in Table 2-2, South African mills generally meet their electricity needs through burning bagasse. It has been noted that with the appropriate government legislation in place, it would be possible for the SA mills to supply excess power into the national grid as well as produce fuel ethanol (SASA, 2017). The SA sugar industry submitted a proposal to the Department of Energy and the National Treasury that indicates a potential to supply a capacity of 1 000MW in the renewable electricity procurement scheme (Tongaat Hulett, 2013). There is a huge potential of re-engineering SA sugar mills to produce their energy requirements using less bagasse, hence increasing bagasse quantities available for further biorefinery activities (Gorgens *et al*., 2015), including electricity and bio-ethanol.

Lu and Yang (2019) state that excess electricity could be directed to the national grid if supporting energy policies are in place. Presently, Brazil contributes 6-8% of bio-electricity to the national grid through sugarcane bagasse combustion (Cervi *et al.*, 2019). Mauritian sugar factories also sell excess electricity from bagasse to the grid during the cane season. In the off-crop season, three of the mills use coal as a complementary fuel to supply electricity to the grid. 318 Gigawatt hours (GWh) of bagasse electricity out of 510 GWh was sold to the grid in 2015. Energy from bagasse cogeneration is targeted to constitute 17% of Mauritius's total electricity supply in 2025 (To *et al*., 2017). Various international energy policies are currently being established to encourage biofuel and bioelectricity generation (Stafford *et al.,* 2019). Securing a sustainable future is paramount, as such, studies investigating the use of straw/sugarcane leaves for bioenergy are on the rise (Cervi *et al*., 2019; Go and Conag, 2019).

2.4.1 The energy cane concept

Solomon and Singh (1995) and Yadav and Solomon (2006) state that many of the sugarcane producing countries world over now appreciate the fact that diversifying sugarcane products is lucrative. In that regard, there is on-going research regarding improvement of the plant for that purpose. The significant and positive contribution of sugarcane as a biorefinery crop can be further enhanced with "*energy cane*," which is a hybrid of wild and commercial sugar cane (IRENA, 2019; Matsuoka *et al*., 2014; Kim and Day, 2011). The fibre content of energy cane is double that of sugar cane and this has environmental and economic advantages (Carvalho-Netto *et al*., 2014). The plants demand less water, nutrients and are more resistant to pests and diseases. They can withstand competition from weeds resulting in efficient cultivation. Energy cane can therefore be planted in areas prone to drought and poor soil as it requires low use of pesticides, herbicides and fertilisers. The plant also has a high multiplication ratio of approximately 1:30 compared to the common rate of sugarcane cultivars of 1:10. In Louisiana, the ratoon cycle for energy cane is longer (15 months) than for conventional sugarcane (normally 10 to 12 months) (Carvalho-Netto *et al*., 2014; Matsuoka *et al*., 2014; Kim and Day, 2011). Under sub-tropical and tropical conditions, it is capable of producing more than 250 tons/ha under rainfed conditions which is much higher in comparison to conventional cane varieties under the same conditions (Matsuoka *et al*., 2014). Countries such as Mauritius and the United States of America are researching and already implementing energy cane in commercial crops (Santchurn *et al.*, 2016; Carvalho-Netto *et al*., 2014; Santchurn *et al*., 2014).

Bonomi *et al.*, 2016 state that there are a number of uncertainties regarding the viability of energy cane. There is still need for more research with respect to its agricultural management, processing and composition efficiencies as well as productivities. Energy cane clones have been seen to have a low unit stem mass, high flowering rates and high occurrence of smut disease calling for effective strategies to overcome these challenges. In addition, Diniz *et al*. (2019) state it is important to consider possible technological constraints in harvesting high fibre cane and the efficiency in industrial processing of this type of cane for broth extraction.

In SA, energy cane could be grown for multi-purpose to produce, for example, fibre for electricity co-generation and molasses for ethanol, in addition to sugar, creating profit from the whole stalk. Considering that some countries are already using the lignocellulosic fraction to produce ethanol using 2G technology (Section 2.4) there is a lot of potential to make use of the additional bagasse for the sugarcane biorefinery. The South African sugarcane industry has not yet started growing this type of cane, but has considered the option, particularly when a regulatory framework or policy for co-generation or ethanol becomes available (M. Zhou, personal communication, January 21, 2019). The current biofuels framework acknowledges that 2G and 3G technology is still underdeveloped in South Africa and states that the first stage of biofuels production in SA will employ first generation technology.

2.4.2 Research outlook on biorefinery product choices

Investment in a multiproduct biorefinery, however, relies on comprehensive economic prefeasibility studies. The selection of which products to include in a multiproduct biorefinery as well as which processes to use requires the use of techno-economic analyses (TEA) methods that will aid in the identification of the economically best performing configurations (Mandegari *et al*., 2017b). A TEA, according to Lauer (2008), is a comparison between costs and benefits using diverse methods for various reasons including evaluating the economic outcome of different technology applications producing similar products. Most TEAs incorporate process simulation models that are used to simulate the energy balances and material of chemical processing plants. Several biorefinery techno-economic analyses (TEA) investigating the economic feasibility of technologies and bio-based product combinations have been published and carried out (Mandegari *et al*., 2017b; Moncada *et al*., 2013; Quintero *et al*., 2012; Dias *et al*., 2009).

In South Africa, Farzad *et al.* (2017) and Gorgens *et al.* (2015) investigated the suitability of certain processes and chemicals to sugarcane biorefinery development using sugarcane residues (trash and bagasse) for six possible scenarios. All sustainability aspects (environmental, economic and social) were assessed and scenario development assumed that the biorefineries would be annexed to existing sugar mills. The scenarios all had the option of electricity sale alongside one other of the following combination of products: bio-ethanol, bio-ethanol and lactic acid, bio-ethanol and furfural, bio-methanol, Fischer-Tropsch syncrude and biobutanol (Gorgens *et al*. 2015). In the study, bio-methanol production and coproduction of ethanol and lactic acid had the highest Internal Rate of Return (IRR). Diederichs *et al.* (2016) performed a techno-economic study for jet fuel production from lignocellulosic feedstock (2G) against two processes from sugar cane juice and vegetable oil. Booysen *et al*. (2017) developed the New Product Greenhouse (NPG) toolbox, which allows for the identification of commercially feasible biorefinery products for the South African setting. The NPG toolbox uses built in algorithms that include economic, market, technology and feedstock competition criteria in the assessment. Although the toolbox enables identification of feasible products, it does not consider capital and operating costs resulting in the need for additional investigations to authenticate the results. Naidoo *et al*. (2019a) further assessed the selected products by incorporating capital expenditure (CAPEX) and operating expenditure (OPEX) costs using the Sugarcane Biorefinery Economic Analysis Toolbox (S-BEAT). The study, which is a second stage to Booysen's work, provides an economic analysis and preliminary cost estimates for the production of selected products. Naidoo *et al*. (2019a) used S-BEAT to investigate the commercial attractiveness of producing high-density polyethylene (HDPE), polylactic acid (PLA), succinic acid, lysine, ethanol and other biorefinery products from different sugar mill streams. The economic indicators utilised in S-BEAT were the Net Present Value (NPV), IRR and discounted Payback Period (PBP). Results from the study showed that lysine, lactic acid and polylactic acid from a syrup stream and ethanol and 1,4-butanediol from clear juice are potentially feasible products.

The above studies are generally based on mass and energy balances followed by various optimization processes that account for cost, size, uncertainty, location and feedstock availability. While they take market prices of the products into account, they do not fully capture the influence of markets (supply and demand issues) and the technology they are investigating on feedstock availability. A new production process may have an impact on resource availability and prices. *Ex ante* studies can bridge this gap through scenario building as well as analysing economic, environmental and social impacts amongst other research possibilities (Sauvee, 2016). Section 2.5 gives an overview of various *ex ante* studies that have been carried out in agriculture and biorefining in order to draw out the methodologies used in this present study.

It is important to note however that the technoeconomic and feasibility SA studies presented in this section informed the choice of biorefinery products used in the study. Selected products were lysine from syrup, bio-ethanol from clear juice and bio-methanol as well as electricity which both could be produced from bagasse. The selection was based on the product combinations for South African mills that had the highest IRR. A brief insight into the markets for these products is explained in the next section.

2.4.3 Bio-Methanol

Methanol is produced globally in Europe, Africa, Asia, Middle East and North and South America. There are currently over 90 methanol plants world over with a total production capacity of an estimated 138 billion litres (110 million metric tons) (Methanol Institute, 2020). The demand for methanol has been partly driven by its wide application in energy, accounting for 40% of methanol consumption and its use as a precursor in chemical synthesis (Methanol Institute, 2020). Other chemicals that can be made from methanol include formaldehyde and acetic acid and these have a wide industrial use. Fuel applications for methanol include marine fuel, vehicle fuel, industrial boiler fuel, and biodiesel (IRENA and Methanol Institute, 2021).

In the United States, blended or pure methanol has been used as a fuel in some vehicles for example race cars since the 1970s (Amigun *et al*., 2011). It is expected that methanol's global production capacity will be approximately 311 million metric tons by 2030 (Statista,2020). Presently throughout the world, over 75% of methanol production is via natural gas conversion, refinery off gas, coal or petroleum (IRENA and Methanol Institute, 2021). In South Africa, SASOL is the only producer of methanol through gasification synthesis. In 2007, the Sasolberg SASOL plant produced 140 000 tons per annum of methanol (Cambray, 2007).

Renewable methanol is produced when the source of energy and feedstock in the production of renewable methanol is of renewable origin. Bio-methanol from biomass and green e-methanol from carbon dioxide (harnessed from renewable sources) and green hydrogen are the two forms of renewable methanol. Producing biofuels through biomass gasification is at early commercial stage and demonstration. According to IRENA and Methanol Institute, (2021) not more than 0.2 Mt of renewable methanol is produced per year. This includes a plant in Netherlands using bio-methane to produce bio-methanol, a large-scale Fischer–Tropsch plant in Enerkem, Canada, using municipal solid waste for bio-methanol production and a geo-thermal plant in Iceland combining carbon dioxide with renewable hydrogen to produce e-methanol.

While methanol can be produced in both large- and small-scale operations, high capital requirements in setting up production facilities call for economies of scale (IRENA and Methanol Institute, 2021). This reduces production cost per unit of methanol produced but increases the quantity of biomass feedstock required. Scaling up of bio-methanol production is highly dependent on consistent supplies of biomass feedstock at a low cost. Cambray (2007) suggests that the easiest entry of bio-methanol into the SA local and export market is through direct use as a fuel or fuel blending, biodiesel production, as aviation fuel, or using methanol cook stoves. SASOL'S methanol is of high purity and is used for biodiesel production in South Africa. Amigun *et al* (2011) highlights that SA's biodiesel market is comprised of a number of small to medium scale producers.

2.4.4 Bio-ethanol

Bio-ethanol or ethyl alcohol is a petrol substitute manufactured from the fermentation of starch/sugar crops such as wheat, barley, sugar cane, maize, sorghum and sugar beet (U.S. Energy Information Administration, 2020). Apart from its other uses as an alcohol, in solvents and the pharmaceutical industry, bio-ethanol is mostly used as a petroleum vehicle fuel alternative. Renewable Fuels Association (2020) shows the United States and Brazil are the largest suppliers of bio-ethanol contributing 84% of the world's supply. Brazil's ethanol is mostly from sugarcane while corn is the major biomass for United States' ethanol production.

In South Africa, SASOL is currently the largest synthetic ethanol producer with an output of 285 million litres per year (Fakir *et al*., 2019). Cartwright (2007) states that in the 1930's to late 1960's bio-ethanol contributed to South Africa's liquid fuel resources, this however proved unviable due to cheap abundant crude oil in the industry. According to Fakir *et al*. (2019), 120 million litres of bio-ethanol are produced annually and NCP Alcohols in Durban is one of the major producers of ethanol from molasses fermentation. It is mainly used in inks and paints, as an alcohol and in the pharmaceutical industry. According to Kholer (2016), 55 to 75 percent of bio-ethanol produced in South Africa is exported to Europe and African countries. Due to its low carbon emission and biodegradability ethanol demand is increasing as countries aim to use environmentally sustainable biofuels (U.S. Energy Information Administration, 2020).

It is estimated that 700 million litres of bio-ethanol could be produced annually in SA if the excess sugar exported to the world market is used for bio-ethanol production. The biofuel blending mandate is a minimum of 2% bio-ethanol into petrol and Fakir *et al* (2019) state that approximately 500 million litres of bio-ethanol would be required annually to meet the demand. A total of 433 million litres of sustainable aviation fuel could also be produced from the bio-ethanol using the alcohol-to-jet pathway.

2.4.5 Bagasse electricity

In 2009, the National Energy Regulator of South Africa (NERSA) approved the Renewable Energy Feed-in Tariff (REFIT) scheme. REFIT compelled Eskom to purchase renewable electricity supplied by qualifying renewable energy producers at a guaranteed price (IEA, 2013; Odeku *et al*., 2011). This renewable energy strategy was revised in 2011 and replaced by the Renewable Energy Independent Power Producer Programme (REIPPP). This involves a competitive bidding process for more than 6 000MW of generation capacity. Qualifying technologies include solar PV, onshore wind, biomass solid, solar thermal, landfill gas, biogas, and small hydro plants (South African Government, 2021). As mentioned in Section 2.4, the SA sugar industry submitted a proposal to the Department of Energy and the National Treasury that indicates a potential to supply a capacity of 1 000MW bagasse electricity (Tongaat Hulett, 2013). However, in a recent announcement on 28 October 2021by the Minister of Mineral and Energy Resources, Mr Gwede Mantashe, preferred bidders mainly for solar and wind energy (IPP Renewables, 2021).

Some sugar producing countries exporting bagasse electricity to the national grid include Mauritius, Brazil, Australia, India, Nicaragua, Colombia, the Phillipines, Guatemala and El

Salvador. Brazil’s cogeneration units support ethanol and sugar sectors when they under perform. In Mauritius 10 of the 11 factories export electricity to the local grid. During the off-crop season, coal is used as a complementary fuel for electricity generation. Success of cogeneration is dependent on stakeholder participation at all levels, good government support in terms of implementing appropriate incentives and policy guidelines and adequate technology. Technological advancement includes but is not limited to more efficient high-pressure boilers that produce superheated steam (Eggleston and Lima, 2015)

2.4.6 Lysine

Lysine is an amino acid used in protein biosynthesis and commercially manufactured as L-lysine hydrochloride usually from a sugar base. More than 75% of the world’s supply is produced as L-Lysine hydrochloride (Brautaset *et al.*, 2017; Connor, 2008). It is one of the nine essential amino acids in humans and is vital for human growth. The amino acid is also an important additive in animal feed (Brautaset *et al.*, 2017; Connor, 2008).

The major world lysine producers are in China, Korea, Germany and USA. As of 2016, China was a giant manufacturer in this industry with 62% market share (Market Watch News Department, 2020). The top four manufacturers include Global Bio-Chem Tech, Cheil Jedang Corp. Ajinomoto Ltd. and Archer Daniel Midland with a production capacity of more than 60% (Grand View Research, 2015). In South Africa, the SA Bioproducts plant with an initial capacity of 10 800 tons per year of l-lysine was operational from 1995 until 2011. By the time lysine production ceased its capacity had increased to approximately 16 000 -18 000 tons per year (SA Bioproducts, 2013). Increased lysine imports and high feedstock prices resulted in the company failing to sustain lysine production (ITAC, 2011).

Further details of how each of these selected products were integrated into the biorefinery appended to the mill model is explained in Chapter 3. The subsequent section includes a description of how *ex ante* studies have been applied in agriculture and the biorefining field.

2.5 *Ex ante* assessments in agriculture and biorefining

Ex ante analysis, also described as a ‘what if analysis’, can take a descriptive or econometric approach depending on the availability of data and resources. A descriptive approach is based on existing statistics providing initial approximations and thus lacks information on the estimated expected impacts (UNCTAD, 2016). Econometric evaluations include estimation with computable general equilibrium models dependent on data from varied sectors of the economy or a microeconomic model, using household, individual or firm level data limited to a specific segment of the economy. This approach enables policymakers to identify causal relationships between policy changes and a given outcome (UNCTAD, 2016).

According to Vidueira (2014) the idea of *ex ante* assessment was introduced to the Organization for Economic Co-operation and Development (OECD) member countries in the late 1990s and the European Commission (EC) adopted it in policy making in 2002 (Shrestha *et al*., 2016; Tscherning *et al*., 2008). *Ex ante* impact assessments of the European Union have been conducted on successive Common Agricultural Policy (CAP) policy reforms to inform the policy design process (Shrestha *et al*., 2016). Mary *et al*. (2013) made use of a dynamic farm household modelling framework to assess *ex ante* the impacts of the implementation of a CAP Income Stabilisation Payments (ISP) in representative French cereals farms. De Graaf *et al*. (2010), following new rules of the CAP for olive oil producers in 2005, carried out an *ex ante* assessment using linear programming to establish the socio-economic and environmental impacts of the new rules for different olive grove development scenarios. Helming *et al*. (2011) developed a framework for *ex ante* impact assessment of a bioenergy policy scenario and CAP policy financial reform scenario on land use in certain European regions using both quantitative and qualitative techniques. Wang *et al.* (2018) carried out a life cycle sustainability assessment *ex ante* to assess the potential sustainability impact of Municipal Solid Waste Management Innovations in Indonesia. Banerjee *et al*., (2016) made use of Computable General Equilibrium (CGE) models to evaluate the *ex ante* economic impacts of public investments in agroforestry development in the Brazilian Amazon. Tran *et al*. (2013) employed the Trade-off Analysis for Multi-Dimensional Impact Assessment (TOA-MD) model to perform an *ex ante* assessment of integrated aquaculture-agriculture adoption in Southern Malawi. Moser and Mußhoff (2016) performed a regression analysis for an *ex ante* study that aimed to test different policy incentives for reducing intensive fertiliser use for small-scale palm oil producers in Indonesia. Dizyee *et al*. (2019) carried out an *ex ante* assessment of two policy interventions aimed at improving the productivity of local-breed cows in Tanzania. They constructed and analysed an integrated system dynamics (SD) simulation model capturing issues such as the economics of milk market access and the impact of rainfall. *Ex ante* evaluations can thus be performed to investigate among other sectors, various agricultural issues using different methodologies.

In the biorefinery field, Baral and Rabotyagov (2017) used an econometric or logistic regression model to assess the demand and market for cellulosic biofuels manufactured from the hybrid poplar. This investigation aimed at establishing a wood-based cellulosic biofuels industry in the US Pacific Northwest. It was observed from their study that biofuels knowledge, offered bid price, religious affiliation and age were important influencers of the respondents' willingness to pay for the cellulosic biofuels. Baral and Rabotyagov (2017) recommended that policies should encourage production of fuel blends and cellulosic biofuels that match the quality perceived by consumers. Brinkman *et al*. (2018) made use of an interregional input-output model to assess the impact of sugarcane-based ethanol production expansion in Brazil on employment, trade and Gross Domestic Product (GDP). Results demonstrated that increasing Brazil's sugarcane ethanol production is likely to boost employment by 53 000 and the national Gross Domestic Product by 2.6 billion USD in 2030 terms. In their study, Schuenemann *et al*. (2017) analysed the economic, environmental and land use impacts on different sectors of the economy of producing biofuels in Malawi using a modelling framework that integrates a computable general equilibrium (CGE) model with two natural resource models. Conclusions drawn from Schuenemann *et al*. (2017) show that irrigated smallholder outgrower schemes are the ideal means for crop production to supply biofuel processors in Malawi. Additionally, while rainfed cropping systems increase poverty levels and have a negative effect on food security, they result in lower greenhouse gas emissions. A dynamic CGE model connected to the microsimulation (MS) model was used to investigate the impact of biofuel investments on poverty, growth, and food security in Ethiopia (Debela and Tamiru, 2016). The results indicated that biofuel investments offer an opportunity for poverty reduction and improved economic growth.

Studies focusing on the potential influence of markets (prices, demand and supply of sugarcane) on sugarcane biorefinery investment decisions are lacking. These aspects should be adequately accounted for via a complementary economic market model. Recent years, as demonstrated in the above literature, have witnessed the creation of a considerable number of impact assessment tools pertaining to sustainability assessment *ex ante* (Haavaldsen *et al*., 2014). These include Environmental Impact Assessment (EIA), ecological footprint, Life Cycle Assessment (LCA), Cost-Benefit Analysis (CBA), scenario tools and multi-criteria decision analysis (e.g. Sustainability Impact Assessment (SIA)) amongst many others (Haavaldsen *et al*., 2013). Brinkman *et al*. (2019) carried out a literature review to identify bioenergy socio-impact indicators and analysed the recently used quantitative *ex ante* research approaches. Identified research methods included Computable General Equilibrium (CGE), Input Output (IO), Partial Equilibrium (PE), Social Accounting Matrix (SAM) and Life Cycle Assessment (LCA), as well as cash flow analysis models. Given this wide spectrum, this research has made use of partial equilibrium modelling which falls under a category of economic models. The following section defines partial equilibrium models and outlines what differentiates them from other models.

2.6 Defining partial equilibrium models

A wide number of economic models in terms of the method used (partial or general equilibrium models, econometric), subject of analysis (trade, environmental or agricultural policy) or the geographical coverage (global, regional or national) have been developed in agricultural economics over the years (Bai *et al*., 2012). Economic modelling has a major role in corporate/strategic environmental planning and national policy-making (Earles and Halog, 2011). Computable general equilibrium models (CGE) models are macro-economic models that use national aggregate data from all sectors of the economy. They capture economic interactions of demand, supply and competition amongst the sectors that direct the sectors to a state of equilibrium (Brinkman *et al*., 2019). CGE models fail to identify variation within sectors. Therefore, where necessary, modification of the model to obtain detailed results becomes crucial. Partial equilibrium models are similar to CGE models in that they use supply and demand laws to attain a new equilibrium. They, however, are more comprehensive and describe particular sub-sectors or agricultural sub-sectors through analysing price interactions, the impact of a policy on the producers' and suppliers' income, and the interdependency of agricultural inputs and outputs between various product lines (Kotevska *et al*., 2013; Janda *et al*., 2012). Partial equilibrium analysis examines the effects of policy action in creating equilibrium only in that particular sector or market which is directly affected. It ignores its effect on other industries or markets, assuming that those impacts are small (Janda *et al*., 2012). As mentioned in Section 2.5, this study uses a partial equilibrium model since special focus is on one sector of the economy, the sugarcane sector. An overview of the use of partial equilibrium modelling in different industries including the sugar industry is outlined in the subsequent section.

2.6.1 Application of partial equilibrium modelling in agriculture

According to Parappurathu (2007), a typical agricultural partial equilibrium (PE) model consists of a producer core system that represents the supply side of the commodity in question and a consumer core system to represent the demand side of the commodity. In this research, the commodity under analysis is sugarcane from which the raw materials (molasses, sucrose, bagasse and other fermentable sugars) required for biorefinery production are sourced. The supply side will be represented by linear programming models of representative sugarcane farms. Likewise, a model of a biorefinery appended to the representative sugar mill will be used to represent the processing of sugarcane and the selected biorefinery products (ethanol, methanol, lysine and electricity generation for sale). The demand by the mill for sugarcane which typically translates to the demand for the feedstock (molasses, sucrose and bagasse) for biorefinery production will be derived from the domestic and export market demands for a representative set of biorefinery products (ethanol, methanol, lysine and electricity generation). The suitability of the partial equilibrium model to incorporate both the producer and consumer core system in one analysis was another reason for its selection.

Partial equilibrium (PE) modelling is frequently used to assess the consequences of a policy or other intervention on a market (Francois and Hall, 1997). Benirschka *et al*. (1996) developed a partial equilibrium model that investigated the effect of trade and farm policies on the world sugar economy. The model simulated sugar supply (area harvested, yield and sugar production) and sugar demand (domestic consumption, net exports and carry out stocks) for more than 10 years for 18 countries. The PE model by Benirschka *et al*. (1996) is a dynamic one and each year a new market equilibrium price was identified. A study by Martinez-Gonzalez *et al*. (2007) used partial equilibrium modelling to assess the impact of imported Brazilian ethanol on the US market. In the field of biorefinery, PE models have been applied in the United States of America (U.S.A.) to assess the national and global impacts of enlarging the biofuel industry (Chen *et al*., 2011; Rajagopal *et al*., 2009). Chen *et al*. (2011) investigated the impact of the Renewable Fuel Standard mandate instituted by the Energy Independence and Security Act in the U.S.A., which requires increased biofuel production by 2022, on feedstock prices, land use application, social welfare and greenhouse gas emissions. Rajagopal (2009) built a partial equilibrium model that estimated the effect of increased biofuel production on sellers and buyers in food and fuel markets. The study also sought to identify the impact of biofuel growth on prices and quantities of food and fuel in these markets. Results of the research showed that biofuels can be responsible for increased food prices and the reduction in supply of crops for food processing (corn and soya). Zhang *et al*. (2013) made use of PE modelling to analyse the impacts of biofuel production and policies on the food prices, trade, welfare impacts and supply on the Organisation for Economic Co-operation and Development (OECD) countries.

In South Africa, a study by Funke *et al*. (2009) used PE modelling to investigate the impacts of the 2007 South African Industrial Biofuels Strategy on biofuel and agricultural subsectors. In this study, policy and macro-economic and factors were shown to influence the success of a biofuel industry. The conclusion was that there is need for adequate government support and conducive macro-economic conditions to ensure success of the biofuel strategy. Adeyemo *et al*. (2011) investigated the impacts of biodiesel feedstock production in South Africa's Eastern Cape Province. The study applied a PE model to the Eastern Cape Social Accounting Matrix with canola production introduced as an 'external shock'. Results revealed that biodiesel production investment is capable of increasing GDP to R18.1 million in 2007 terms. Moreover, 410 job opportunities per year would be created and a positive balance of payment was noted (Adeyemo *et al*.,2011). Much of this research has only focussed on one product of a biorefinery (biofuels) at macro-economic level, yet many more downstream products can be produced in a biorefinery. This could probably be because of an increasing demand for energy, high oil prices and a growing world population making biofuels an alternative source of energy (Janda *et al*., 2012). Additionally, most of the fossil resources are actually used for energy purposes, and only a small percentage (10-15%) go to chemical production there is a high technology readiness level for energy provision in the biorefining field.

This present study has identified this gap and uses a partial equilibrium model to assess the impact of further developing sugarcane biorefineries on biorefinery product investment options and on the supply and demand of sugarcane in the South African context. This includes incorporating bio-methanol, bio-ethanol and lysine production as well as additional bagasse electricity in biorefinery processing other than the conventional sugar and molasses that are currently produced. This study will look into the sustainability of sugarcane biorefineries by considering the interaction of prices, sugarcane demand and supply for different scenarios. These comprise a scenario representing the status quo in the industry where only sugar and molasses are incorporated in the division of proceeds, a scenario where bagasse, molasses and sugar as well as the selected biorefinery products in South Africa are included in the division of proceeds. Another scenario where energy cane is included in the analysis is presented.

Research models have different strengths and weaknesses and at times models are integrated to account for the weaknesses of the other (Brinkman *et al.*, 2019). Part of this study's objective is to establish the on-farm implications of selected biorefinery investments on sugarcane production. PE models fail to describe the effects of policy measures that directly impact farms, as such, integration of farm and PE models of biorefinery scenarios solves this weakness. This study integrates a farm-level linear programming model together with partial equilibrium tools.

2.6.2 Studies integrating the farm and biorefinery in one model

Studies linking the biorefinery and farm models are supported by research showing that commercialisation of biorefineries capable of handling 5 000 to 10 000 MT daily of biomass requires a reliable and secure feedstock supply system (Carolan *et al.*, 2007). Biorefineries need sufficient feedstock with reliable quality at the right time, at competitive prices to ensure reasonable profits for biomass suppliers and converters (Liu *et al.*, 2015; Carolan *et al.*, 2007). Sendich and Dale (2009) state that farmers will not produce large quantities of biomass unless they can envisage the profitability from their supply of feedstock. On the other hand, biorefinery investors will not make huge investments unless they are assured of long term consistent feedstock supplies that are reasonably priced. Some studies integrating biorefinery and agricultural production models have been carried out. Sendich and Dale (2009) created a Biorefinery and Farm Integration Tool which combined a biorefinery model with animal and crop (agricultural) production models. This permitted an economic and environmental analysis of possible secondary products, fertilizer production, bioenergy and biomass production amongst several regions of the United States (Sendich and Dale, 2009).

Shreshtha *et al.* (2016) highlights that agro-economic models have played a crucial role in the *ex ante* analysis of agricultural policies. Farm models capable of representing new Common Agricultural Policy (CAP) instruments and measuring farm-level effects are receiving increased interest. Farm-level analysis allows for greater flexibility and capturing of farm heterogeneity which is not possible with general and partial equilibrium frameworks (Shreshtha *et al.,* 2016).

2.7 Application of farm-level models

The farm is central to agriculture decision making and farm-level models are increasingly being used to capture farmer reactions to different policy scenarios due to their ability to take into account interactions between farm activities and potential farm adaptations in response to economic, institutional or technological changes (Shrestha *et al.*, 2016). There are various farm-level modelling approaches ranging from farm supply models focussing mainly on economic objectives, agricultural household models that include the social dimension and bioeconomic models which combine environmental and economic objectives. Farm adjustments or adaptations refer to changes that occur in the resources, activities or management of the farm when exposed to external changes (Shrestha *et al.*, 2016). These adaptations can be modelled using mathematical and statistical farm-level modelling techniques. Examples of statistical models include the Ricardian method, multivariate probit models and multinomial logit models. Created by Mendelsohn *et al*. (1994), the Ricardian method has been used in a number of studies to examine the economic impact of climate on agriculture, specifically on farm revenues and land values (Deressa, 2007; Mano and Nhemachena, 2007; Gbetibouo and Hassan, 2005; Polsky and Easterling III, 2001). Logit and Probit models are most commonly used in analysing farmer agricultural technology adoption but have also been used in climate change studies (Deressa, 2008). These models make use of observed/empirical data and aim to establish relationships between dependent and adaptation variables which are first identified before their inclusion in the model (Muzamhindo *et al.*, 2015; Gbetibouo, 2009; Nhemachena and Hassan, 2008). According to Shrestha *et al.* (2016), the major weakness of statistical models is that they overlook the fact that in reality, a farmer makes decisions based on the compounding effects of modifying different activities on the entire farming system mainly because of the interlinkages of activities (Shrestha *et al.*, 2016).

Mathematical models include decision models such as the agent-based model (ABM) and optimisation models. ABM models are capable of determining the impact of non-monetary influences and social factors on decision making using a set of agents or decision making entities that interact with their environment and amongst each other (Matthews *et al.*,2007; Bonabeau, 2002). In agriculture, they have been widely applied in land use decision making (Guillem *et al.*, 2015; Murray-Rust *et al.*, 2014; Matthews *et al.*, 2007). In most cases, the model examines the impact of an already identified adaptation which can be a limitation in the event that an adaptation measure is unknown (Shrestha *et al.*, 2016). Linear programming (LP), non-linear programming (NLP) and mixed integer programming (MIP) models are examples of optimisation models. These models simulate the farmers' decision making through optimizing objectives and adjusting various farm management activities (Shrestha *et al.*, 2016). Optimisation mathematical models usually make use of mathematical programming (MP) for solving problems to assist in decision making and in *ex ante* simulation of agricultural policies. MP, according to Hazell and Norton (1986) is an optimisation approach that allows policy instruments to be modelled at farm or regional level, enables farm heterogeneity to be captured and permits representation of various interactions within farming activities and practices. This study makes use of LP programming to build representative farm-level models for three regions to be outlined in the next chapter.

The computational efficiency of linear programming enables LP models to be widely used in determining farm-level adaptations (Shrestha *et al.*, 2016; Önal *et al.*, 2009). The LP model is built using detailed farm-level data that includes physical and financial information for an individual or representative farm (Shrestha *et al.*, 2016). Van Calker *et al.* (2004) used farm-level LP programming to determine the effect of environmental policy and farm management adjustments on various sustainability indicators for a Dutch Dairy farm. Net farm income was an indicator for measuring economic sustainability while ecological sustainability was measured using seven indicators, some which include acidification potential, global warming potential and water use. In a study by Acs *et al.* (2007), a dynamic linear programming model was developed for a Netherlands typical arable farm. The research was based on observation that most farmers do not convert to organic farming despite its profitability compared to conventional farming. Acs *et al.* (2007) mentions that farmers and policy makers are unaware of the factors that can hinder or encourage conversion from conventional to organic farming due to lack of information. The model's objective maximised the net present value over a ten year plan and the aim was to investigate the impact of different factors that limit the conversion process. Linear programming has thus been used as an optimisation decision making tool in industries specifically agriculture. In this present study, a partial equilibrium model using linear programming was constructed so as to establish an optimal solution for the interaction of biorefinery product prices, mill investment decisions and corresponding grower decisions. The implications of different cane payment scenarios on the division of proceeds under selected biorefinery options constituted a part of the analysis. In Chapters 4 of this thesis, a detailed description of the linear programming methodology used to build the farm and biorefinery appended to the mill model (BAM) is outlined. Farm models have to simulate reality in the closest way possible. Risk is an important factor to consider and the subsequent section describes this in detail.

Integrating risk into farm models

In order for farm LP models to accurately model farmers' decisions, there is need to consider risk and farmers' risk preferences. Farming is generally a risky business that is affected by the unpredictability of weather conditions, uncertain input and output prices and changes in government regulations and policies (Hardaker *et al.*, 2015). The main risk sources in the SA sugarcane industry include amongst many others, recurrent droughts, low world sugar prices, reduced demand following the introduction of the Health Promotion Levy (HPL), and dumped imports from countries such as Brazil (SACGA 2019; BFAP, 2015; Mac Nicol *et al.*, 2007). Risk adds complexity to the farm decision making process and accounting for it can have a positive impact on business performance (Backus *et al.*, 1997). As such, it was important to integrate risk in the farm representative model.

Farmers are generally risk-averse, meaning they behave in ways that could assist in reduction of risk. This could imply forgoing some expected income while taking up farm plans that offer some security (Dent *et al.*, 2013). The risk-averse nature of farmers can be exhibited in the form of buying insurance of varied forms, diversification of enterprises or unwillingness to take up new technologies (Hardaker *et al.*, 2015). Considering risk-averse behaviour in the model increases the accuracy of results. Different risk programming techniques are used to incorporate risk in decision making. These include Expected Income Variation (E-V analysis), Minimisation of Total Absolute Deviations (MOTAD), Target MOTAD, Baumol's E-L criterion and Game Theory models. These models hinge on the notion that farm plans have different income distributions and the farmer's choice is inclined towards a farm plan that best meets their goals (Hazel and Norton, 1986). According to Barnard and Nix (1988), the most common programming techniques are Baumol's criterion and MOTAD. Baumol's E-L criterion is closely linked to MOTAD, the only difference being that it incorporates a risk aversion coefficient (ϴ) in the model. Risk is viewed as a cost measured by ϴ where a higher value of ϴ depicts greater risk resulting in a much diverse farm plan (Hazel and Norton, 1986). The risk aversion coefficient can be known or unknown. In cases where it is unknown, estimates from literature is imputed. This, however, may lead to bias and data errors or underestimation of the ϴ value if farmers are exposed to risk-sharing institutions (Hazel and Norton, 1986). Farmers are required to select plans with the highest expected income for a given utility level. The criterion assumes that a farmer maximises utility at a certain level of risk aversion. The study adopted the Baumol's model and a description of the methodology is highlighted in Chapter 3. To represent the demand side of the PE model, a representative mill model was built using linear programming. The next section gives an overview of linear programming in manufacturing or operations, thus proving the suitability of its use in this study.

2.8 Overview of linear programming in manufacturing

Linear programming (LP) has been widely used in operations research to solve many managerial problems (Rader, 2010). Azapagic and Clift (1998) used LP to identify the Best Practicable Environmental Option for the borates product system in order to optimise the environmental performance of borate products in the Improvement Assessment Phase of Life Cycle Assessment. Veslovska (2014) presents an integrated linear programming model applied on a real life production process with cost minimization as the main objective. The production process involved three products with three different production processes sharing the same space and resources. LP enabled identification of critical points of the production process providing managers with information that guides their decision making. Mokebe and Joubert (2013) applied Mixed Integer Linear Programming (MILP) in the optimisation of a pulp stock production process. Through the technique, an optimum system throughput, the network to be used, and the preferred landfill site at a given landfill disposal and stream operating cost are determined. Campo *et al*. (2018) implements an LP aggregate production planning model to minimise total costs linked to inventory and labour levels taking into account different characteristics that contribute to operational efficiency in textile production.

In biorefining, linear programming has mostly been used for supply chain optimization regarding water use, greenhouse gas emissions, net energy use, and profitability. Xie at al. 2010 integrated an MILP model into a GIS- based decision support tool to find the optimal biorefinery locations with an objective of minimising biomass transportation cost. Zondervan *et al*. (2011) presented a Mixed Integer Non-Linear Program (MINLP) biorefinery optimization model to establish an optimal processing route in the production of butanol, ethanol and blends of these chemicals with gasoline. Ubando *et al*. (2012) used a fuzzy linear programming model (FLP) to optimise and design an algal biorefinery that considers carbon, water and land footprints. This present study will use a biorefinery appended to the mill (BAM) representative LP model to represent the processing of sugarcane at a biorefinery as well as include a set of representative products potentially feasible to produce at an SA sugarcane biorefinery.

Literature review summary

The literature review shows that progress has been made to improve sustainability of the South African sugar industry by signing of the Sugarcane Value Chain Master Plan to 2030. Although the Master Plan supports product diversification through sugarcane biorefinery establishment, there is need to investigate the economic viability of a biorefinery with regards to feedstock supply and market price interactions of the products. It is clear from the review that there are strong economies of size in biorefinery investments. The economic viability of a biorefinery is dependent on there already being sufficient feedstock delivered to the mill, or providing incentives to growers to supply the biorefinery with sufficient feedstock. The review identifies that studies focusing on the potential influence of markets (prices, demand and supply of sugarcane) on farm-level and sugarcane biorefinery investment decisions are lacking. Farm-level decisions that can change for sugarcane growers include choice of cultivars grown, the production methods, and when and how it is harvested. These aspects should be adequately accounted for via a complementary economic market model.

Out of the various research methods identified in literature, partial equilibrium modelling is the most suitable to this type of study. Partial equilibrium models are comprehensive and describe particular sub-sectors or agricultural sub-sectors through analysing price interactions, the impact of a policy on the producers' and suppliers' income, and the interdependency of agricultural inputs and outputs between various product lines. The study uses a partial equilibrium model to assess the impact of different biorefinery product investment options on the supply and demand of sugarcane in the South African context for the Eston cane supply area. This work looks into the sustainability of sugarcane biorefineries by considering the interaction of prices, demand and supply of sugarcane and selected biorefinery products for different cane payment system scenarios.

An assessment of the different cane payment and division of proceeds scenarios employed by selected countries already in sugarcane biorefining showed that the type of revenue sharing agreement and the products included in revenue sharing can differ. It was interesting to note that, countries incorporating biorefinery products in the division of proceeds successfully produce the products e.g. electricity generation in Mauritius, bio-ethanol in Brazil and Colombia. In addition, the review also demonstrates that there is room for flexibility in establishing a cane payment system depending on the incentives being driven by a specific country's sugar industry. In Colombia for example, there are three types of cane payment systems depending on the miller grower situations. Lastly, key drivers of economic sustainability in the countries' cane industries anchor on timely and continuous development of appropriate strategies and policies followed by coordinated action plans and enhancement of diverse revenue streams. Some of the policies include financial and tax incentives to stimulate biofuel production, marketing, regulation of ethanol and biodiesel domestic consumption mandates, minimum blending regulations, fuel price setting, encouragement of manufacture of flex-fuel vehicles by the government and provision of interim subsidies to cane growers during stressful times. It is important to note that in Brazil, the need for government support through subsidies or any other form has been minimised as private investments fund alcohol mill construction.

Colombia's sugar production occurs all year round allowing the country to meet local demand without supply interruptions. This review established that a high fibre variety of cane, energy cane could be grown for multi-purpose to produce, for example, fibre for electricity co-generation and molasses for ethanol, in addition to sugar, creating profit from the whole stalk. Some countries are already using the lignocellulosic fraction to produce ethanol using 2G technology there is a lot of potential to make use of the additional bagasse for the sugarcane biorefinery in South Africa.

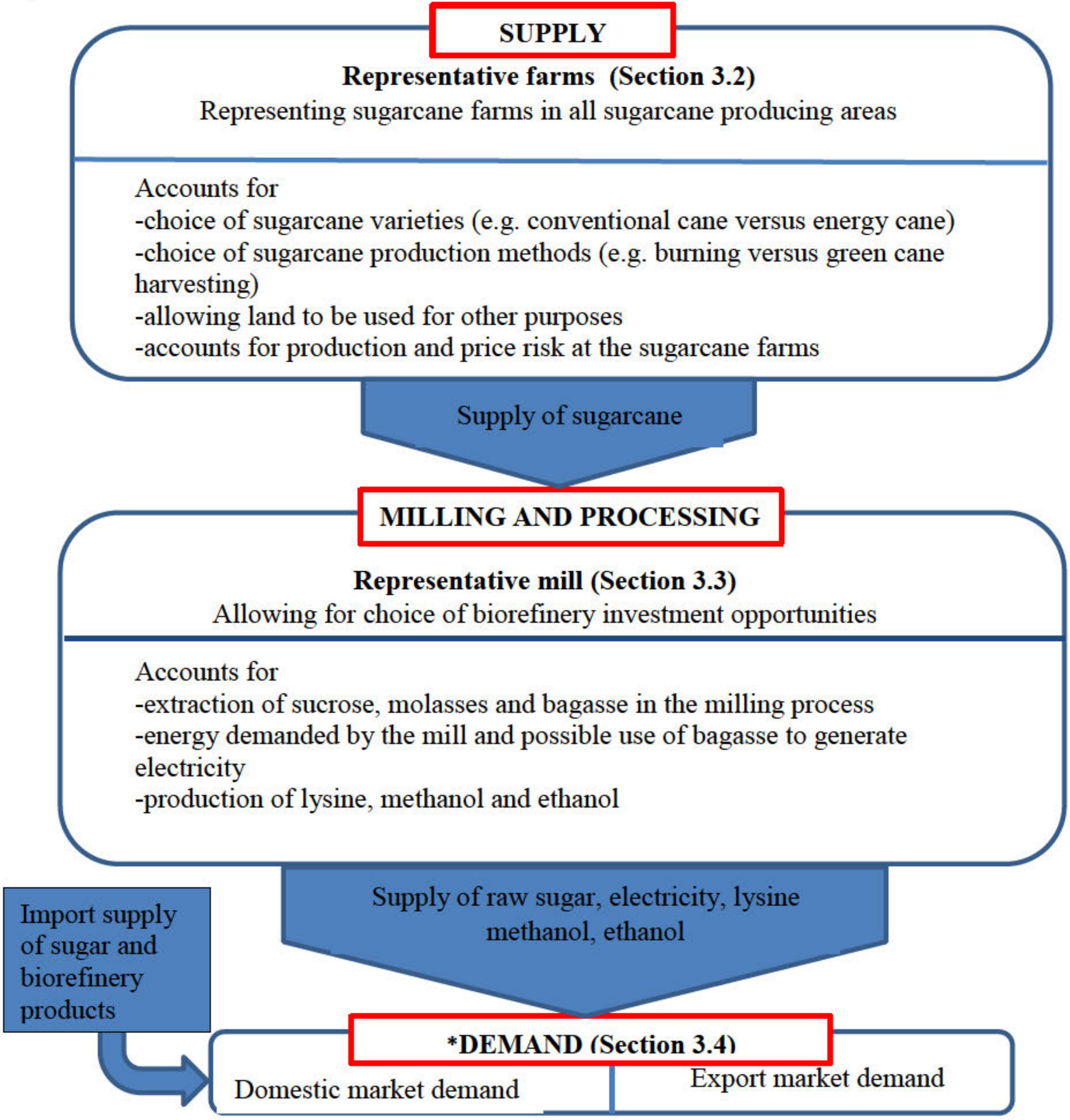
Technoeconomic and feasibility studies carried out in South Africa informed the choice of biorefinery products used in the study. These include lysine from syrup, bio-ethanol from clear juice and bio-methanol as well as electricity which both could be produced from bagasse. These studies are generally based on mass and energy balances followed by various optimization processes that account for cost, size, uncertainty, location and feedstock availability. While they take market prices of the products into account, they do not fully capture the influence of markets (supply and demand issues) and the technology they are investigating on feedstock availability. A new production process may have an impact on resource availability and prices. *Ex ante* studies were identified to bridge this gap through scenario building as well as analysing economic, environmental and social impacts amongst other research possibilities.

Partial Equilibrium modelling was identified to be the appropriate tool for this type of study. The Partial equilibrium model (PE) in this study will look into the sustainability of sugarcane biorefineries by considering the interaction of prices, sugarcane demand and supply for different scenarios. However, PE models fail to describe the effects of policy measures that directly impact farms, as such, this is circumvented by integrating farm and PE modelling tools. This study therefore integrated PE modelling tools with farm level models. In the next chapter, the methodology for construction of the partial equilibrium and farm level models is described.

3. RESEARCH METHODOLOGY

This chapter presents the methodology used to gather data necessary to build the representative farm and mill models as well as details of how the models were constructed. The study uses a partial equilibrium model as highlighted in Chapter 2. According to Parappurathu (2007), a typical agricultural partial equilibrium (PE) model consists of a producer core system that represents the supply side of the commodity in question and a consumer core system to represent the demand side of the commodity. In this research, the commodity under analysis is sugarcane which is a raw material for the biorefinery products that can potentially be produced from sugarcane processing. PE models are capable of representing the production, trade and demand for agricultural products. They however fail to describe the effects of policy measures that directly impact farms. Integration of farm-level models and PE models solves this weakness resulting in a model with robust results. As such, the supply side of the PE model will be represented by linear programming models of representative sugarcane farming areas within one selected milling region. Likewise, a model of a biorefinery appended to a sugar representative mill will be used to represent the processing of sugarcane and production of selected biorefinery products. The demand for molasses, sucrose and bagasse from sugarcane by the mill will be derived from the domestic and export market demands for a representative set of products that could be produced by a sugarcane biorefinery (methanol, ethanol, lysine, electricity generation by the mill for possible sale). The study's focus is on one milling area in the Midlands region of sugarcane growing in South Africa, the Eston area.

Figure 1 is a diagrammatic representation of the supply and demand components of the partial equilibrium model. This is what guided the outline of this chapter.



*Demand component accounts for the relationship between price and quantity demanded in each market for each product

Figure 1 Framework of the supply and demand components of the partial equilibrium model

The first section of this chapter describes how the study area was selected and provides a brief background of the area. The methodology by which data required to build the farm representative models was gathered is also presented in Section 3.1.

3.1 Background to the case study region

The South African sugarcane farming region consists of 14 cane supply areas in three different regions, namely irrigated, coastal and the Midlands (SACGA, 2018). Due to the complexity and differences in climate and production systems across the regions, it was not possible to devise a representative farm model of the whole sugarcane industry (Botha and Berg, 2009). A milling area with a mill that has no backend refinery yet was suitable for this study. Gledhow, Umfolozi and Eston are some of the mills without backend refineries. For the study, the researcher selected a nearby mill, the Eston mill, which is approximately 37km from the researcher's institution.

Information on the Eston region was obtained from a number of sources. This included literature and grower delivery data from the Cane Testing Services (CTS). Key informant interviews were held with the extension officer and Eston area manager, a South African Cane Growers Association (SACGA) representative.

Location and climatic description of the Eston milling area

Established in 1994 and a part of Illovo Sugar Limited, the Eston sugar mill is located in the Midlands area, KwaZulu-Natal Province in Pietermaritzburg (Figure 2). Average annual temperatures are within the 18 to 19°C range and average annual rainfall is from 800 to 900mm (Kadwa, 2014; Lumsden, 2000). According to Sugar industry statistics, the mill is operational for an average of approximately 37 weeks of the year. The total amount of cane crushed in the 2020/21 season added up to about 1.32 million tons which translates to a sugar output of 142 787 tons (SACGA, 2021b). The Midlands region is supported by 416 large-scale farmers and 1 706 small-scale farmers with Eston comprising 900 small scale growers and 190 large scale growers (SACGA, 2019; Kadwa, 2014).

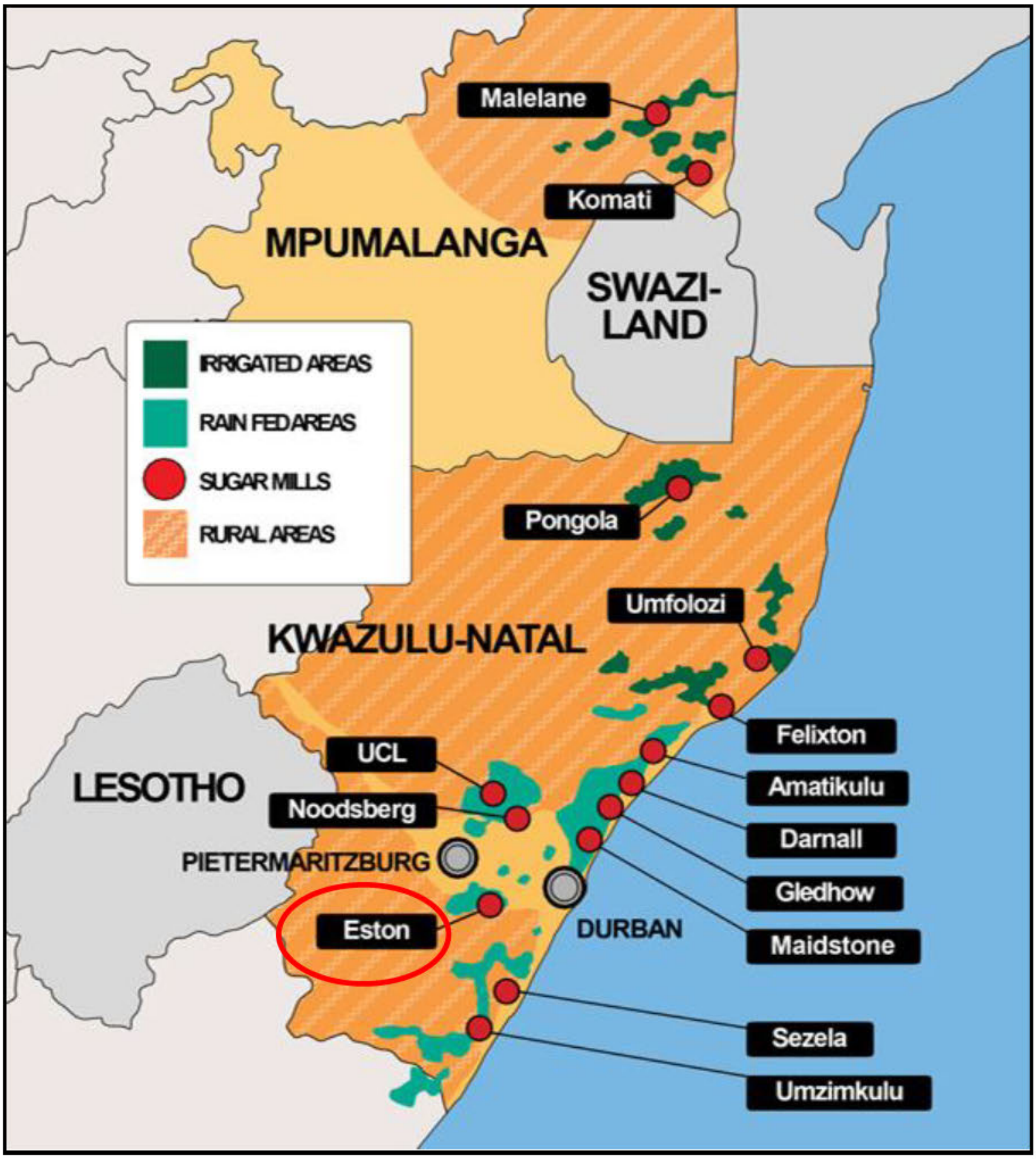


Figure 2 A map of the sugarcane supply areas of the South African sugar industry in the KwaZulu-Natal Province, (SASA 2021)

Most of the areas supplying sugarcane to the Eston mill lie within the Mkhambathini municipality. Eston has six homogenous climatic zones (HCZs) (Bezuidenhout and Gers, 2002), namely Umlaas Road, Baynesfield, Tala Valley, Eston Central, Mid-Illovo and Umkomaas. Figure 2 illustrates five of these zones (SASRI, 2018; Bezuidenhout and Singels, 2007). Mean temperatures in Umlaas, Bainsfield and Umkomaas (Richmond area) range from 13.4-17.5°C while Eston, Tala Valley and Mid-Illovo's temperatures are in the region of 17.5-

21°C. There are also slight differences in rainfall with Mid-Illovo receiving an average of 1 012-1 251 mm/annum, Eston and Tala Valley (Eston Central) 722-826 mm/annum, and Richmond (Umlaas, Baynesfield and Umkomaas) 791-914 mm/annum (Pillay, 2014). Consultations with the extension officer and SACGA's Eston regional manager showed that there is not much variation in the sugarcane farming practices across the areas despite minor differences in climatic conditions. There are, however, differences in yield levels per hectare of sugarcane as well as the harvest transportation costs of cane from the farm to the mill. Thus, the Eston region can be categorised into three regions based on climate, proximity to the mill and yield. These regions are Eston Central (Tala Valley and Eston), Mid-Illovo and Richmond (Umlaas, Baynesfield and Umkomaas). The analysis in this thesis is based on these three regions.

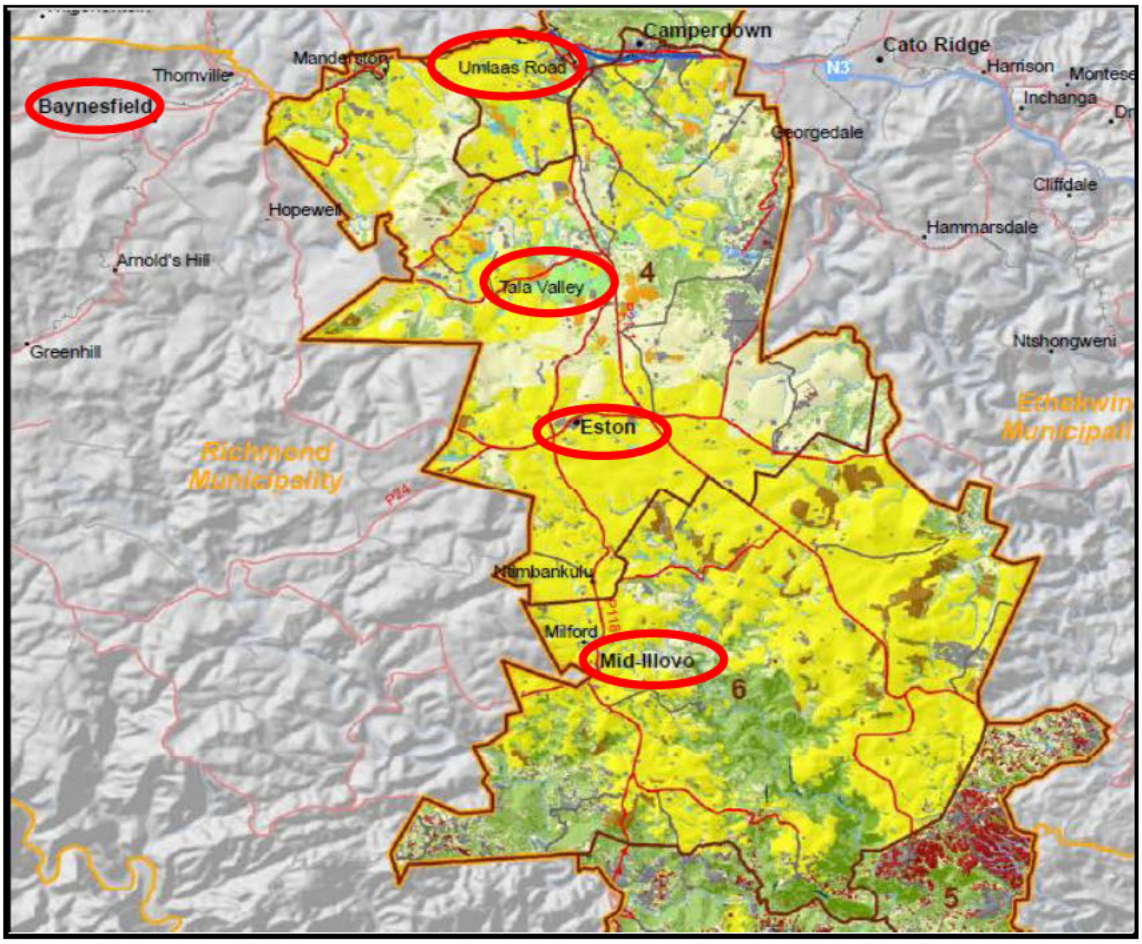


Figure 3 A map of the sugar growing regions (in yellow) within the Eston sugarcane supply area, Mkhambathini municipality, Pillay (2014)

The second objective in the study highlights the need to understand the adoption of sugarcane varieties, cane and recoverable value yield performance, choice of sugarcane production and harvesting methods as well as opportunity cost of land in the Eston milling region. This information forms the foundation of the background data required in constructing representative farms (objective iii). Using the purposive non-probability sampling technique (Tongco, 2007), 33 large scale growers (11 in each region) were selected based on their willingness to participate, availability of historical farming records and diversification both in cultivar selection and other enterprises other than sugarcane. Large scale growers in this study are those farmers delivering more than 10 000 tons of sugarcane per season (Hurly *et al*., 2015; Mac Nicol *et al*., 2007). These growers supply more than 90 percent of the total cane delivered to the mill and as such were regarded as representative of the management and performance of growers in the area. Eston's Mill Group Board gave permission to access the growers cane delivery historical data from Cane Testing Services (CTS). Data accessed was for the seasons 2011/12 to 2017/18 and included the delivery date, cane cultivar, tons of cane per delivery, Recoverable value (RV) and fibre content of the cane. Cane yield data was obtained by conducting in-depth interviews with at least one grower in each region. The number was limited to one as the majority of growers were unavailable for the interviews, as such, certain years did not have information since some farmers would not have harvested a particular cane cultivar or had no records of a cultivar's performance. In order to reduce inaccuracies that can result from inadequate cane yield data, consultations with the SASRI extension specialist and SACGA'S area manager' assisted with finalisation of this data.

Data cleaning was done using Excel functions on a separate worksheet. Information not relevant to the analysis such as the sugar mill number, the week of sugarcane delivery, crush and delivery date was removed. The average cane tonnage per delivery, RV and fibre values were calculated using Excel tools for each cultivar for the three regions. Descriptive statistical tables and graphs summarising cane supply, cane cultivar adoption and cane yield and RV for popular varieties identified from data for the observed years were constructed in Microsoft Excel ® for each region. Summaries of these are provided in the results and discussion chapter (Chapter 4).

This section enabled background information required to build the farm representative models for the study region to be collected. The subsequent section explains the methodology used in building the farm representative models.

3.2 Building the farm representative models

Farmers are challenged with resource constraints and often have to rearrange resources in order to optimise the outcome of their objectives (Shrestha *et al.*, 2016). Changes in external factors such as market prices, agricultural policies, climate and new technology can potentially lead to changes in production decisions amongst farmers. As highlighted in the literature review Section 2.5, farmers and policy makers are interested in carrying out *ex ante* assessments of the consequences of their choices regarding farm plan and policy (Zander and Kächele, 1999). Farm representative models will allow for an *ex ante* assessment of the farm-level impact of appending downstream biorefinery operations to existing South African sugar mills.

A representative/typical farm is a study unit with characteristics similar to a large number of farms and can be used for research activities, estimation of product supply functions and determination of improved farming operations. Three mathematical linear programming representative farm models of a ‘typical’ sugarcane farm for the three regions Eston Central, Mid-Illovo and Richmond, as identified in Section 3.1.1 were constructed. They each represented the baseline scenario and sugarcane supply of the Eston milling area. As outlined in Chapter 1 of this thesis, a biorefinery scenario in the SA sugar industry can potentially use bagasse, sucrose and other fermentable sugars as feedstock for the production of various products. Once bagasse can be used for biofuel production or electricity supply to the national grid it may be necessary to include a high fibre cane variety to increase raw material availability. An alternative scenario including a hypothetical cultivar of cane, energy cane, was incorporated in each of the three farm models as part of the methodology. A detailed description of this is presented in Section 3.4.

3.2.1 Model construction

According to Buysse (2006), a mathematical linear programming model can be described as follows:

Maximize $f(x_j)$ (3.1)

Subject to

$$g_i(x_j) \leq b_i \qquad (3.2)$$

Where:

fx_j - is the objective function reflecting the goals set by decision makers (in this case farmers)

x_j - are the decision variables or activities

bi - are the resources that a farmer is endowed with and,

g_i - is the indication of the contributory factor of each decision variable to resource use.

Additionally, gross margin data for the identified activities is an important building block for LP modelling. In this section, an outline of how each of these key requirements were determined and incorporated into the models is specified beginning with the objective function. Due to similarities in the methodology used to build these models, most of the information presented will be for the Eston Central region and, where necessary, reference will be made to the appendix section where data for the other three regions is presented.

3.2.2 The objective function

The objective function of the models constructed in this section is maximisation of gross earnings for the grower subject to different resource constraints. The main resources considered were both fixed and variable resources that include land, labour, capital, machinery, seed, fertiliser, chemicals and other variable inputs necessary for production. The objective function equation is provided at a later stage at the end of this chapter once different components of the model are outlined.

3.2.3 Identification of farm activities

Csáki (1985) states that an agricultural production system incorporates the use of various resources and technology to produce an agricultural product under specific natural and physical conditions. It can represent a particular agricultural enterprise with specific activities that are coordinated to accomplish set goals. Understanding the production activities surrounding production of sugarcane in the Eston area was important in building the farm representative LP models (Hazel and Norton, 1986). Ten Berge *et al.* (2000) define an activity in an LP model as a “coherent set of operations with corresponding inputs and outputs.” Beneke and Winteraer (1973) also state that a researcher has great flexibility in the choices of activities to input in their model. The structure and number of activities is dependent on the answers sought by the researcher. Each activity contributes towards the realisation of set objectives and this contribution is expressed in the form of technical coefficients in the model. This present study seeks to identify the farm-level impact of potential biorefinery establishment thus selected activities centred on those that are likely to change when the mill's demand for sugarcane is driven by biorefinery establishment.

Nijs (2014) define a production cycle as the time interval between beginning the production process and obtaining the final product. The sugarcane production cycle would therefore include the following activities: planting, ratoon management, harvesting, plow out and green manuring. At the planting stage, sugarcane is grown from cuttings also known as seed sugarcane. After the first harvest, the cane crop is left to re-grow allowing it to produce a number of ratoon crops that are subsequently harvested at specific time periods (Renouf *et al.*, 2010). Cutting cycles in South African sugar growing regions range from 12 to 24 months with the Midlands region cycle falling within that range (SACGA, 2019). Overall, the growth cycle with one plant crop can be as long as 10 to 12 years with four to five ratoon crops. Thereafter, the plant cane is plowed out after which the piece of land can be left fallow or put under green manure (Rhodes *et al.*, 2012). The green manuring crops in Eston are sunhemp/oats or a mix of the two (P. Botha, personal communication, July 18, 2017). CTS data showed that more than 90% of the cane is burnt while the remainder is mixed or green cane harvested. Harvesting is done manually using the cut and stack method after which it is transported to a loading zone, and further to the mill in sugarcane trucks. The cane tops from harvesting are used as a trash blanket. For the purposes of the study, planting and harvesting activities were considered. This is because changes are expected to occur mostly on choices of cane cultivars grown and harvesting methods.

It is possible that once the product portfolio expands to include other biorefinery options, farmers will be inclined to grow certain cane cultivars over others depending on where the value is placed in the sugarcane plant (Waclawovsky *et al.*, 2010), for example sucrose, other fermentable sugars and/or fibre. Different cane cultivars are used depending on the landscape and soil type, thus the planting activities were categorised using soil type and cane cultivar grown. Alternative uses of land (opportunity cost) for sugar cane production formed other activities that would be included in the model. Alternative enterprises in Eston were identified to be cattle, timber, macadamia nuts, oranges and vegetable production. In this study, only macadamia and timber production were considered in model building as they were more common and are perennial crops similar to sugarcane thus directly competing for resources.

Cane cultivar selection is partly dependent on the landscape and soil type; thus, the planting activities were categorised using soil type and cane cultivar grown. Through interviews, the extension officer and area manager of the Eston area assisted in the identification of the various land categories, cane cultivars grown in those categories, the opportunity cost of land and the total available hectarage per land category. This information and popular cultivars grown with more than 7% of total deliveries to the mill in the 2017/18 season were included in the model. Tables 3-1, 3-2 and 3-3 describe the land categories, soil types, cane cultivars, expected yield per annum and opportunity cost of land in the three regions.

Table 3-1 Land categories, soil types, cane cultivars and opportunity cost of land in Eston Central

ESTON CENTRAL			
Land categories and soil types			
	Marginal land poor soil (MP)	**Flat land sandy soil (FS)**	**Flat land clay soil (FC)**
Cane Cultivars	N12, N31	N31, N54	N48, N50
Expected tonnage/annum/ha	80	80	90
Alternative uses of land	timber	macadamia nuts	macadamia nuts
Total available hectares (22550)	12 050	6 000	4 500

Table 3-2 Land categories, soil types, cane cultivars and opportunity cost of land in Mid-Illovo

MID-ILLOVO				
Land categories and soil types				
	Marginal land poor soil (MP)	**Flat land sandy soil (FS)**	**Flat land clay soil (FC)**	**Steep land red soil (SR)**
Cane Cultivars	N12, N31	N52, N12	N48, N54, N12	N50, N54
Expected tonnage/annum/ha	95	110	N48, N54 - 130 N12-100	110
Alternative uses of land	timber	macadamia nuts	macadamia nuts	timber
Total available hectares (12 800)	800	1 000	8 000	3 000

Table 3-3 Land categories, soil types, cane cultivars and opportunity cost of land in Richmond

RICHMOND				
	Land categories and soil types			
	Marginal land poor soil (MP)	**Flat land sandy soil (FS)**	**Flat land clay soil (FC)**	**Steep land red soil (SR)**
Cane Cultivars	N12, N31	N52, N54	N48, N54, N37, N35 (on frost prone land)	N50, N37, N48
Expected tonnage/annum/ha	95	110	N48, N54, N37, N35-130 N12-100	110
Alternative uses of land	timber	macadamia nuts	macadamia nuts	timber
Total available hectares (3150)	750	600	1 000	800

In the model, the farmer represents the supplier of sugarcane which is separated into sugar, molasses and bagasse during the milling process. Selling activities of sucrose and molasses were incorporated in the baseline scenario of the model as a means to capture what the growers are actually paid for in the cane payment system. A selling activity for bagasse (representing the fibre in the cane) was also included to analyse a scenario in which sugarcane fibre is included in the cane payment system. The bagasse is assumed to have a moisture content of 50.8% according to Guest (2018), therefore bagasse and fibre have a direct relationship of 1 ton of fibre equals to two tons of wet bagasse. Additional activities were incorporated when risk was included. The following section explains incorporation of risk in detail.

3.2.4 Accounting for risk and farmers' risk preferences in the model

This research adopted the Baumol's criterion as a risk programming technique in the farm representative models. Baumol's criterion uses deviations in farm gross margins to estimate maximum utility and represent risk (Hazell and Norton, 1986). Gross margins are the difference between income/revenue and variable costs before accounting for other fixed costs (Kay *et al*., 2012). They are essential both for measuring risk and as a key component in LP programming. Price, yield and production cost data are requirements in the construction of gross margins.

This data is relevant in representing risk since growers' production decisions are partly based on future yield and price expectations (Tomek and Kaiser, 2014).

In this study, in addition to land uses such as macadamia nuts and timber production, each cultivar of sugarcane grown in a different category of soil is regarded as a separate land use activity. Gross margins for each enterprise in the three regions were calculated using price, yield and production cost data. With respect to sugarcane, RV nominal prices for seven years from 2012 to 2018 were extracted from the South African Cane Growers Association (SACGA) website. These were adjusted to real values using producer price indices from the Abstract of Agricultural Statistics 2018 (DAFF, 2018; Tomek and Kaiser, 2014). Cane and RV yields for the Eston cane supply area were gathered for seven years (2011/12 to 2017/18) for popular cultivars from growers and Cane Testing Service (CTS). The results for these are presented in Section 4.3. Cane planting, harvesting and ratoon management cost schedules from SACGA for the seven seasons were used to represent input costs necessary for budget construction. Green manuring and pest and disease control costs were obtained from discussions with the (South African Sugar Research Institute) SASRI extension specialist and SACGA area manager and adjusted for inflation to the current year 2018.

The extension officer stated that for a 24-month cycle, about 52% of the cane is harvested and 10% of the area is planted annually. It was necessary to establish what percentage of cane is under ratoon management, green manure as well as is plowed out annually for both 24- and 18-month cycles. This information was important in the construction of annualised budgets that accurately represented what is on the ground. A schedule of all activities in each month (planting, ratoon management, harvesting, plow-out and green manuring) were simulated in Excel for an eight-year cycle of cane since that is when cane is normally plowed-out in Eston. Using the count if function, the number of times each activity is done over the eight-year cycle was established and the percentage per year calculated. Table 3-4 below shows the estimates as they were used in budget construction. A planting estimate of 11, 25% in a 24 month cycle implies that in that cycle the possibility of planting is 11,25%. The 18-month cycle estimates were used only for cultivar N54 while budgets for all other cultivars used 24-month cycle estimates.

Table 3-4 Percentage annual activity estimates for a 24- and 18-month cycle of cane.

Activity	24-month cycle estimates (%)	18-month cycle estimates (%)
Plant	11,25	11,11
Ratoon	40,00	55,56
Harvest	51,25	66,67
Plow out	11,25	11,11
Green manure	11,25	8,33

Gross margin budgets were constructed for all seasons for the popular cultivars. Table 3-5 is an example of a gross margin budget for cultivar N12 in marginal poor soil in Eston Central for five of the seasons. The gross margin budgets for the popular cane cultivars in Eston Central, Mid-Illovo and Richmond on a per hectare basis are in Appendices A, B and C.

Table 3-5 N12 marginal poor soil enterprise budget Eston Central/year/hectare

Year	**2017/18**	**2016/17**	**2015/16**	**2014/15**	**2013/14**
RV price (R/ton)[a]	3817,90	4187,11	5053,05	3460,59	3095,81
Average RV yield (tons/ha)[b]	0,12	0,13	0,11	0,11	0,13
Average cane yield (tons/ha)[c]	100,00	77,13	85,30	61,39	91,64
Income (R/ha) ([a*b*c]*51.25%) ***	22851,99	21414,91	23739,54	12454,13	18867,26
Allocated Costs					
Cane planting costs-Mechanical land prep (Rands)					
Land preparation	3253	2824	2630	2840	2583
Hand planting	2770	2565	2406	2793	2625
Seedcane	8699	6866	6158	5540	5018
Fertiliser and lime	7525	7705	6884	4153	4379
Weed control	2677	2498	2272	2522	1878
Sundries and contingencies	2493	2246	2035	2677	1648
Total cane planting costs[d]	27417	24704	22385	20525	18131
([d]*11.25%) ***	3084,41	2779,20	2518,31	2309,06	2039,74
Harvesting costs (Rands)					
Cutting of burnt cane	5877,00	4213,46	4370,75	2920,92	4098,17
Infield-cane haulage	2528,00	1713,77	1666,75	1319,88	1723,76
Loading and transhipment of burnt cane	1402,00	1093,66	988,62	798,07	1108,85

Total harvesting costs[e]	9807,00	7026,13	5038,86	6930,78	6541,67
([e]*52%) ***	5026,09	3600,89	2582,42	3552,02	3352,60
Ratoon management costs: Dryland cane early harvest (Rands)					
Field management	528,28	524,37	469,87	433,18	403,69
Fertilizer	3233,00	3232,97	3125,82	3042,17	2957,79
Weed control	2463,00	2486,68	2331,64	2167,17	2009,21
Sundries and contingencies	622,46	622,46	585,25	565,87	532,93
Total ratoon costs[f]	6847,03	6711,45	6348,11	6050,44	5498,96
([f]*40%) ***	2738,81	2684,58	2539,25	2420,17	2199,58
Green manuring[g]	3440,24	3543,83	3910,82	4020,91	3749,03
([g]*11.25%) ***	387,03	398,68	439,97	452,35	421,77
Eldana control[h]	2028,75	2028,75	2028,75	2028,75	2028,75
Total variable costs	13265,09	11492,10	10108,69	10762,36	10042,44
Gross margin	9586,90	9922,81	13630,85	1691,76	8824,82

*** indicates that values in that row have been weighted using activity estimates for a 24 month cycle in Table 3-4

Yield and price data from 2011/12 to 2017/18 for macadamia and timber were obtained from growers and experts in these enterprises. Establishment, maintenance and harvesting costs were the major variable costs used in the enterprise budgets for macadamia and timber. Appendices L and M show the annualised gross margin budgets for macadamia and timber production.

Following construction of gross margins, a mean gross margin over the seven years under consideration (2011/12 to 2017/18) was computed for each enterprise for the three regions. Deviations from the mean (both negative and positive, labelled D1 to D7) for all enterprises were calculated for each year (2011/12 to 2017/18, labelled T1 to T7) and were added to the models as activities. Baumol's uses these deviations in farm gross margins to estimate maximum utility and represent risk (Hazell and Norton, 1986).

After defining the activities, the next stage was to identify the constraints. Constraints are defined within the model to represent the limited resources which are the inputs, and an optimal solution is achieved through adjustment of the various activities within the constraints in order to realise the farm objectives (Shrestha *et al.*, 2016; Janssen and van Ittersum, 2007).

3.2.5 Setting the constraints

The main limiting resource identified was land, it was assumed that labour can be hired when required and that capital is not limiting. The identified categories of land were set as the different land resource constraints in each region. On each category there is a maximum amount of land that can be used for planting purposes. This data of the total area available for each category was obtained from Eston's extension officer and is indicated in Tables 3-1 to Table 3-3 in Section 3.2.3. Using the Local Pest, Disease and Variety Control Committee Rules from SASRI, a constraint stating that no single variety should occupy any more than one third of the total area under cane, was added to the model. Furthermore, a constraint stating that the area planted under macadamia cannot exceed 15% of the total arable land was added. This is because some growers in the region are diversifying by reducing their area planted to sugarcane and planting macadamia orchards. The current high profit margins realised from macadamia production may overestimate the possibility of such profits in the long run considering the uncertainty of its future market. Consequently, according to the SACGA area manager, most growers seem reluctant to plant more than 15% of their land to macadamias. Timber on the other hand, requires an afforestation permit to grow timber making it a restriction for growers to expand area under timber or venture into timber production. Those who are producing timber, however, view the enterprise as a great store of liquidity considering that the trees are harvested after eight years and in other cases (e.g. pine trees) 20 years, or more (P. Botha, personal communication, August 22, 2018)

In the same column where constraints appear there are transfer rows which demonstrate in the model how the output or service of one activity can be shifted to a different activity (Beneke and Winterboer, 1984). In the model, these rows appear in the same place as the constraints although they perform a different function. In a biorefinery scenario, sucrose and other fermentable sugars, bagasse and molasses become feedstock for the production of various products with an economic and agro-industrial value to different sectors of the South African economy. While the grower sells cane, in order to capture what the grower is actually paid for in the division of proceeds, all three models include transfer rows for tons of bagasse, sucrose and molasses produced to depict the transformation of tons of bagasse, sucrose and molasses produced from different cane cultivars into sales of the three products. Other fermentable sugars were excluded because there is no biorefinery product that will be produced from any of them and thus will not be included in the division of proceeds.

Furthermore, deviations in each time period (T1-T7) from adding the risk component are also added to the constraints column. Tables 3-6 and 3-7 summarise all the activities and constraints as they were formulated in the model for Eston Central with inclusion of risk. Activity and constraints summaries for Mid-Illovo and Richmond are in Appendices D and E.

Table 3-6 Activity and Constraints summary Eston Central (EC)

Activities (let Xi denote an activity)					
Index	Definition	Index	Definition	Index	Definition
$X_{1\ ha}$	Cultivar N12 in marginal poor soil (MPN12)	X_{20}	D7 (Deviation in time period 7)	B_{16}	Deviation in Time period 4(T4)
$X_{2\ ha}$	Cultivar N31 in marginal poor soil (MPN31)	X_{21}	0.5TAD (Total absolute deviations)	B_{17}	Deviation in Time period 5(T5)
$X_{3\ ha}$	Cultivar N31 in flat sandy soil (FSN31)	X_{22}	SD (Standard deviation Rands)	B_{18}	Deviation in Time period 6 (T6)
$X_{4\ ha}$	Cultivar N54 in flat sandy soil (FSN54)	Constraints (let Bi denote constraint)		B_{19}	Deviation in Time period 7(T7)
$X_{5\ ha}$	Cultivar N48 in flat clay soil (FCN48)	B_{1}	Marginal poor soil		
$X_{6\ ha}$	Cultivar N50 in flat clay soil (FCN50)	B_{2}	Flat land sandy soil		
$X_{7\ ha}$	Timber in marginal poor soil (MPTimber)	B_{3}	Flat land clay soil		
$X_{8\ ha}$	Macadamia nuts in flat sandy soil (FSMac)	B_{4}	Sucrose transfer		
$X_{9\ ha}$	Macadamia nuts in flat clay soil (FCMac)	B_{5}	Molasses transfer		
X_{10}	Sucrose selling (Rands)	B_{6}	Bagasse transfer		
X_{11}	Molasses selling (Rands)	B_{7}	Macadamia nut constraint		
X_{12}	Bagasse (representing fibre) selling (Rands)	B_{8}	Cultivar N12 constraint		
X_{13}	Expected Gross Margin (Rands)	B_{9}	Cultivar N31 constraint		
Gross margin deviations (Di) in Rands		B_{10}	Cultivar N54 constraint		
X_{14}	D1 (Deviation in time period 1)	B_{11}	Cultivar N48 constraint		
X_{15}	D2 (Deviation in time period 2)	B_{12}	Cultivar N50 constraint		
X_{16}	D3(Deviation in time period 3)		Deviations in Time periods (T_i)		
X_{17}	D4 (Deviation in time period 4)	B_{13}	Deviation in Time period 1 (T1)		
X_{18}	D5 (Deviation in time period 5)	B_{14}	Deviation in Time period 2 (T2)		
X_{19}	D6 (Deviation in time period 6)	B_{15}	Deviation in Time period 3 (T3)		

Table 3-7 **Summary of identified constraints and definitions with corresponding linear equations as they were incorporated in the model for Eston Central**

List of constraints (let *Bi* denote a constraint)		
Index	**Definition**	**Corresponding equation**
Resource constraints		
B1	*Marginal poor soil*	$X_1 + X_2 + X_7 \leq 12050$
B2	*Flat land sandy soil*	$X_3 + X_4 + X_8 \leq 6000$
B3	*Flat land clay soil*	$X_4 + X_5 + X_6 + X_9 \leq 4500$
Transfer rows		
B4	*Sucrose transfer*	$-6{,}5X_1 - 6{,}2X_2 - 6{,}5X_3 - 10{,}9X_4 - 7{,}2X_5 - 6{,}6X_6 + X_{10} = 0$
B5	*Molasses transfer*	$-2X_1 - 1{,}9X_2 - 2X_3 - 3{,}4X_4 - 2{,}5X_5 - 2X_6 + X_{11} = 0$
B6	*Bagasse transfer*	$-15X_1 - 14{,}2X_2 - 15X_3 - 25{,}2X_4 - 16{,}5X_5 - 15{,}2X_6 + X_{12} = 0$
Planting activity constraints		
B7	*Macadamia nut constraint*	$-0{,}15X_1 - 0{,}15X_2 - 0{,}15X_3 - 0{,}15X_4 - 0{,}15X_5 - 0{,}15X_6 - 0{,}15X_7 + 0{,}85X_8 + 0{,}85X_9 \leq 0$
B8	*Cultivar N12 constraint*	$0{,}67X_1 - 0{,}33X_2 - 0{,}33X_3 - 0{,}33X_4 - 0{,}33X_5 - 0{,}33X_6 \leq 0$
B9	*Cultivar N31 constraint*	$-0{,}33X_1 + 0{,}67X_2 + 0{,}67X_3 - 0{,}33X_4 - 0{,}33X_5 - 0{,}33X_6 \leq 0$
B10	*Cultivar N54 constraint*	$-0{,}33X_1 - 0{,}33X_2 - 0{,}33X_3 + 0{,}67X_4 - 0{,}33X_5 - 0{,}33X_6 \leq 0$
B11	*Cultivar N48 constraint*	$-0{,}33X_1 - 0{,}33X_2 - 0{,}33X_3 - 0{,}33X_4 + 0{,}67X_5 - 0{,}33X_6 \leq 0$
B12	*Cultivar N50 constraint*	$-0{,}33X_1 - 0{,}33X_2 - 0{,}33X_3 - 0{,}33X_4 - 0{,}33X_5 + 0{,}67X_6 \leq 0$

Table 3-8 Summary of identified constraints in the Eston Central model with corresponding equations

Deviation in time periods constraints	
Index	**Definition**
B_{13}	T1 (Rands) $3475,5X_1 + 1798,8X_2 + 2133,8X_3 + 4498,9X_4 + 3367,4X_5 + 1792,3X_6 - 630,76X_7 - 11223,09X_8 - 59370,3X_9 + X_{14} \geq 0$
B_{14}	T2 (Rands) $2009X_1 - 2466,2X_2 + 2192,8X_3 + 3952X_4 - 1726X_5 + 1311,2X_6 - 415,7X_7 - 4746,5X_8 - 42140,4X_9 + X_{15} \geq 0$
B_{15}	T3 (Rands) $-1003,7X_1 - 114,4X_2 + 221,3X_3 + 1453,4X_4 - 2227,1X_5 + 1007,7X_6 - 341,2X_7 - 86,4X_8 - 9300,4X_9 + X_{16} \geq 0$
B_{16}	T4 (Rands) $-8136,8X_1 - 8128,3X_2 - 6877,5X_3 - 11468,2X_4 - 2522X_5 - 6861,2X_6 + 76,4X_7 + 3636,1X_8 + 13628,1X_9 + X_{17} \geq 0$
B_{17}	T5 (Rands) $3802,33X_1 - 879,6X_2 - 1490X_3 - 1425,6X_4 + 2019,2X_5 + 3107,7X_6 + 30X_7 + 2378,1X_8 + 22861,2X_9 + X_{18} \geq 0$
B_{18}	T6 (Rands $94,28X_1 + 3574,4X_2 + 2394,6X_3 + 6787,7X_4 + 512,6X_5 + 1029,1X_6 + 494,9X_7 + 4403,1X_8 + 33819,3X_9 + X_{19} \geq 0$
B_{19}	T7 (Rands) $-241,6X_1 + 1283X_2 + 1425,1X_3 - 3797,3X_4 + 575,9X_5 - 1387X_6 + 786,4X_7 + 5638,6X_8 + 40502,7X_9 + X_{20} \geq 0$

The constraints and corresponding equations for Mid-Illovo and Richmond are in Appendices D and E. The main differences are in the land categories and cultivars grown on the land and coefficients.

Table 3-9 shows the planting activities of the cane cultivars, timber and macadamia under different land categories as they appeared in Excel. The right-hand side (RHS) for the land categories represents the maximum quantity of land available in each category. The bagasse transfer row highlights, for example, that for every 1 ha of N12 harvested 15 tons of bagasse are produced. Conversion values of these products was done using manufacturing ratios for a 'generic' model of a South African raw sugar mill outlined in Guest *et al*. (2019).

Table 3-9 Mini-tableau for Eston Central showing sugarcane cultivars, opportunity cost of land, selling activities and resource constraints.

Land categories and constraints	**Cane variety grown/ha**			**Opportunity cost/ha**			**Sales (tons)**	
	MP N12	FS N31	FC N48	MP Timber	FS Mac[a]	FC Mac[a]	Bagasse	RHS[b]
Marginal land Poor Soil (MP)	1							≤12050
Flat land Sandy soil (FS)		1			1			≤4500
Flat land Clay soil (FC)			1			1		≤6000
Bagasse transfer (tons)	-15	-15	-17				1	=0
Macadamia constraint	-0,15	-0,15	-0,15	-0,15	0,85	0,85		≤0
N12 constraint	0,67	-0,33	-0,33					≤0
N31 constraint	-0,33	0,67	-0,33					≤0
N48 constraint	-0,33	-0,33	0,67					≤0

[a] Mac: Macadamia. [b] RHS: Right Hand Side

Table 3-10 Mini-Tableau showing incorporation of the risk component for all three models

GM[a] deviations	MPN12 ha	Bagasse sales	E[GM] [b] Rands	D1[c] Rands	D2 Rands	0.5 TAD[d]	SD[e] Rands	RHS
T1[f] (Rands)	3475,48			1				≥0
T2 (Rands)	2009,99				1			≥0
Sum (Rands)				-1	-1	1		=0
Conv (Rands)						-F[g]	1	=0
E[GM]Acc Constraint	-10752[i]	1000[j]	-1					=0
OBJ[h]: L= E[GM]-θσ			1				-1,65	Max!

[a] GM: Gross Margin. [b] E[GM]: Expected Gross Margin. [c] D1: Deviation in time period T1. [d] TAD: Total absolute deviations. [e] SD: Standard deviation. [f] T1: Time period 1 deviation. [g] Correction factor (F). [h] Objective function. [i] Variable costs of production for N12 per hectare. [j] Bagasse selling price per ton.

The sum row (Table 3-10) adds up all deviations and translates them into total absolute deviations, expressed by the equation for Eston Central:

B $_{20}$ Sum (Rands) $$-X_{14} - X_{15} - X_{16} - X_{17} - X_{18} - X_{19} - X_{20} + X_{21} = 0$$

where X_{14} D1 (Deviation in time period 1 in Rands)

X_{15} D2 (Deviation in time period 2 in Rands)

X_{16} D3 (Deviation in time period 3 in Rands)

X_{17} D4 (Deviation in time period 4 in Rands)

X_{18} D5 (Deviation in time period 5 in Rands)

X_{19} D6 (Deviation in time period 6 in Rands)

X_{20} D7 (Deviation in time period 7 in Rands)

X_{21} 0.5TAD (Total absolute deviations)

The conversion factor row (conv) (Table 3-10) has a correction factor F that converts 0.5TAD into an estimate of standard deviation using the equation:

$$F = 2\Delta^{0.5}$$

where $$\Delta = \pi T/2(T-1)$$

where T is the total number of seasons under observation, in this case seven seasons from 2011/12 to 2017/18.

In the model, $\Delta=\pi7/2(7-1) = 1,83$

Therefore, $F=2(1,83)$^0.5

$= 0,39$

B_{21} **:** $-0,39X_{21} + X_{22}$

Where X_{21} is 0.5TAD (Total absolute deviations) and X_{22} is SD (Standard deviation measured in Rands)

The last row in Table 3-10 shows the objective function equation as

$$L=E[GM]-\theta\sigma$$

where L is the utility or minimum income achieved with a certain probability (e.g. 85 or 95%), E[GM] is the expected gross margin, θ is the growers' risk aversion coefficient, and σ is the standard deviation of E.

the E[GM] equation in the model is expressed as ***B_{22}*** :

$$-13265,1X_1 - 12880X_2 - 12880X_3 - 20397X_4 - 15623X_5 - 13463.19X_6 + 3428X_7 + 20793X_8 + 46888X_9 + 3200X_{10} + 1000X_{11} + 500X_{12} - X_{13} = 0$$

Where

X_1	Cultivar N12 in marginal poor soil (MPN12) (hectares-ha)
X_2	Cultivar N31 in marginal poor soil (MPN31) (ha)
X_3	Cultivar N31 in flat sandy soil (FSN31) (ha)
X_4	Cultivar N54 in flat sandy soil (FSN54) (ha)
X_5	Cultivar N48 in flat clay soil (FCN48) (ha)
X_6	Cultivar N50 in flat clay soil (FCN50) (ha)
X_7	Timber in marginal poor soil (MPTimber) (ha)
X_8	Macadamia nuts in flat sandy soil (FSMac) (ha)
X_9	Macadamia nuts in flat clay soil (FCMac) (ha)
X_{10}	Sucrose selling (Rands)

X_{11} Molasses selling (Rands)

X_{12} Bagasse selling (Rands)

X_{13} Expected Gross Margin (Rands)

The coefficients in the above equation for X_1 to X_6 are the different total variable costs of production for the different sugarcane cultivar enterprises while coefficients for timber and macadamia production (X_7 toX_9) are the enterprises' gross margin values. Coefficients for X_{10} to X_{12} are the selling prices for the products sucrose molasses and bagasse, they can be altered.

For Eston Central, the objective function was

$$\boldsymbol{X_{13}} - 1{,}645\boldsymbol{X_{22}}$$

Where $\boldsymbol{X_{13}}$ is the expected gross margin and $\boldsymbol{X_{22}}$ is the standard deviation

Risk (σ) in this case is treated as a cost weighted by the risk aversion coefficient (θ). This means the larger the value of θ, the heavier the weight attached to risk resulting in a more diversified farm plan. The risk aversion coefficient is usually unknown beforehand and is prone to change as management decisions are made. Using t statistics tables, the risk aversion coefficient (θ) in this study was identified by selecting an income value that generates a farm plan with the closest fit with the actual farm plan under a baseline scenario. On that note, the probability of achieving a favourable income with a close fit for Eston Central and Mid-Illovo was at 95% while that for Richmond was at 85%. These values correspond with risk aversion coefficients of 1,645 and 1,036 respectively. This means at risk aversion coefficients of 1,645 or 1,036, a favourable income with a close fit is achieved 95% or 85% of the time respectively.

3.2.6 Model verification and optimisation

To verify accuracy of the three representative farm models, the white-box validation method according to Robinson (1997) was used. This involves establishing whether model components accurately represent real world components through inspecting output reports. A comparison was made between the current adoption of popular cane cultivars as of August 2018 in the three regions and the model output current scenario. Tables 3-11 to 3-13 demonstrate these values.

Table 3-11 A comparison of real and model percentage adoption for Eston Central

Cane cultivar	N12	N31	N48	N54	N50	N52	N37	N16	N41
Real % adoption	39,61	18,2	12,12	7,49	7,14	3,67	2,14	1,65	1,16
Model % adoption	33	20	15	14	3	-	-	-	-

Table 3-12 A comparison of real and model percentage adoption for Mid-Illovo

Cane cultivar	N12	N48	N54	N37	N31	N16	N52	N50
Real % adoption	46,49	13,02	8,48	5,79	4,77	2,39	1,51	1,26
Model % adoption	25	33	23	-	4	-	-	-

Table 3-13 A comparison of real and model percentage adoption for Richmond

Cane cultivar	N37	N48	N12	N54	N31	N35	N41	N52	N50	N36
Real % adoption	25,59	24,36	13,07	9,18	8,66	5,94	5,67	3,64	1,41	1,19
Model % adoption	24	33	24	16	-	-	-	3	-	

The model represented quite well what is on the ground with slight variation in the area under N54 and N48. The model projects more area under N54 than is currently on the ground in Eston Central Region. This is a new variety whose adoption has consistently increased yearly since its introduction in 2015. It has high cane yields that are realised over a shorter grower cycle, a characteristic which cane growers have indicated is the reason for its increased adoption.

After verification, gross margins were then optimised subject to the identified constraints under two scenarios. The first scenario represented the current status quo in the SA sugar industry where only conventional sugarcane varieties are grown as well as only molasses and sucrose are included in the division of proceeds A sensitivity analysis was performed on the first scenario using different bagasse price scenarios. Results of this stage are presented and discussed in Chapter 4. As part of this study’s objective, a second scenario was added to the models, and this was with inclusion of energy cane.

3.2.7 Incorporation of energy cane in the farm representative models

In order to add energy cane to the models, it was treated as an additional activity to the model. Applying the same methodology used in Sections 3.2.3 and 3.2.4, gross margin budgets for energy cane for each representative farm were prepared for seven seasons 2011/12 to 2017/18. Literature and South African Sugar Research Institute (SASRI) expert opinion formed the basis from which these budgets were constructed. In South Africa, energy cane would likely yield about 10% sucrose, 15 to 20% fibre and a high non-sucrose fraction (M. Zhou, personal communication, January 21, 2019).

While energy cane produces high tonnage that can be over 200t/ha, the growth cycle is highly dependent on the agro-ecological region where the variety is grown (Kim and Day, 2011). In the irrigated region and coastal areas, achieving a high tonnage in less than 12 months would be possible, while in the Midlands areas, energy cane may achieve high tonnage in about 15 to 18 months ((M. Zhou, personal communication, January 21, 2019). Based on this information, energy cane was assumed to have a growth cycle of 18 months and possible cane and RV yields were estimated under the guidance of SASRI expert opinion, these are outlined in Table 3-13. As a starting point in this study, the variety was assumed to only be planted in the poor soils based on literature that showed the plant's ability to grow on marginal soils (Kim and Day, 2011).

Table 3-14 shows cane and RV yield estimates that were used to construct energy cane gross margin budgets for seven seasons (2011/12 to 2017/18). Cost schedules from SACGA were used since the production cost of energy cane was not expected to deviate much from what is currently being practised. For the purposes of comparing yield differences between energy cane and conventional cane varieties, Table 3-14 also includes cane and RV yields for conventional cane varieties for all three regions of the Eston Cane supply area.

Table 3-14 Estimates of cane and RV yield for 2011/12 to 2017/18 seasons for energy cane and conventional cane varieties

Energy cane average RV and cane yields						
	Eston Central		Mid-Illovo		Richmond	
Year	**Cane yield (tons/ha)**	**RV yield (tons/ha)**	**Cane yield (tons/ha)**	**RV yield (tons/ha)**	**Cane yield (tons/ha)**	**RV yield (tons/ha)**
2011/12	120	0,08	173	0,09	154	0,09
2012/13	160	0,07	187	0,07	170	0,08
2013/14	190	0,09	170	0,08	160	0,07
2014/15	180	0,07	135	0,07	140	0,06
2015/16	130	0,06	122	0,06	130	0,07
2016/17	140	0,07	194	0,07	150	0,08
2017/18	170	0,08	200	0,09	185	0,07
Conventional cane average RV and cane yields						
2011/12	99	0,13	112	0,14	101	0,13
2012/13	104	0,13	105	0,13	110	0,13
2013/14	92	0,13	110	0,14	129	0,13
2014/15	61	0,11	100	0,13	64	0,11
2015/16	85	0,11	116	0,12	83	0,11
2016/17	77	0,13	119	0,13	114	0,12
2017/18	100	0,12	127	0,13	128	0,12

Gross margin budgets for energy cane in each region are shown in Appendices A, B and C.

3.2.8 Activities, constraints and risk with energy cane

Activities and constraints identified in Section 3.2.3 for the representative models were not altered. The only difference was the addition of energy cane growing under marginal poor soil as an additional activity. A similar methodology to the one highlighted in Section 3.2.4 was used to incorporate risk in the representative models with energy cane for all three regions. Gross margin deviations from the mean for seven seasons (2011/12 to 2017/18) were calculated for energy cane and added to the model. An example of a mini-tableau with some activities including energy cane as it appeared in Excel for Eston Central is shown in Table 3-15 below.

Table 3-15 Mini-tableau for Eston Central showing some activities and constraints with energy cane included

Land categories and constraints	**Cane variety grown/ha**			**Sales (tons)**			
	MP N12	MP Energy cane	FC N48	Sucrose	Molasses	Bag[a]	RHS[b]
Marginal land Poor Soil (MP)	1	1					≤12050
Flat land Clay soil (FC)			1				≤6000
Sucrose transfer (tons)	-6,50	-6,80	-7,15	1			=0
Molasses transfer (tons)	-2,00	-0,34	-2,20		1		=0
Bagasse transfer (tons)	-15	-44,20	-16,5			1	=0
Macadamia constraint	-0,15	-0,15	-0,15				≤0
N12 constraint	0,67	-0,33	-0,33				≤0
Energy cane constraint	-0,33	0,67	-0,33				≤0
N48 constraint	-0,33	-0,33	0,67				≤0

[a]: Bagasse [b]: Right Hand Side

The columns in Table 3-15 show some of the activities in Eston Central. Each category of land was the main resource constraint and additional constraints were for macadamia and the different cultivars stating that no more than a third of the area should be under one cultivar. Transfer rows were also included in the model, to account for the transformation of cane into the sale of bagasse, sucrose and molasses. The conversion rates of bagasse, sucrose and molasses for energy cane were estimated around the ratios of sucrose: 9,6%, non-sucrose: 0,2% and fibre at about 26,7 % dry weight (Kim and Day, 2011). In Table 3-15 for example, one hectare of energy cane harvested produces 6,8 tons sucrose, 0,34 tons molasses, and 44,2 tons of bagasse. An outline of all variables inserted in the model with energy cane for Eston Central is shown in Table 3-16. This table is very similar to the first scenario (Table 3-6), the only difference being the introduction of energy cane.

Table 3-16 List of variables inserted in the model with energy cane for Eston Central

Activities (let Xi denote an activity)	
X_1	*Cultivar N12 in marginal poor soil (MPN12) (ha)*
X_2	*Energy cane in marginal poor soil (MPEC) (ha)*
X_3	*Cultivar N31 in marginal poor soil (MPN31) (ha)*
X_4	*Cultivar N31 in flat sandy soil (FSN31) (ha)*
X_5	*Cultivar N54 in flat sandy soil (FSN54) (ha)*
X_6	*Cultivar N48 in flat clay soil (FCN48) (ha)*
X_7	*Cultivar N50 in flat clay soil (FCN50) (ha)*
X_8	*Timber in marginal poor soil (MPTimber) (ha)*
X_9	*Macadamia nuts in flat sandy soil (FSMac) (ha)*
X_{10}	*Macadamia nuts in flat clay soil (FCMac) (ha)*
X_{11}	*Sucrose selling (Rands)*
X_{12}	*Molasses selling (Rands)*
X_{13}	*Bagasse selling (Rands)*
X_{14}	*Expected Gross Margin (Rands)*
***Gross margin deviations* (*risk*)**	
X_{15}	*D1 (Deviation in time period 1in Rands)*
X_{16}	*D2 (Deviation in time period 2 in Rands)*
X_{17}	*D3(Deviation in time period 3 in Rands)*
X_{18}	*D4 (Deviation in time period 4 in Rands)*
X_{19}	*D5 (Deviation in time period 5 in Rands)*
X_{20}	*D6 (Deviation in time period 6 in Rands)*
X_{21}	*D7 (Deviation in time period 7 in Rands)*
X_{22}	*0.5TAD (Total absolute deviations)*
X_{23}	*Standard deviation*
Constraints	
B_1	*Marginal poor soil*
B_2	*Flat land sandy soil*
B_3	*Flat land clay soil*
B_4	*Sucrose transfer*
B_5	*Molasses transfer*
B_6	*Bagasse transfer*
B_7	*Macadamia nut constraint*
B_8	*Cultivar N12 constraint*
B_9	*Energy cane constraint*
B_{10}	*Cultivar N31 constraint*
B_{11}	*Cultivar N54 constraint*
B_{12}	*Cultivar N48 constraint*
B_{13}	*Cultivar N50 constraint*
Time periods (risk)	
B_{14}	*Deviation in Time period 1 (T1)*
B_{15}	*Deviation in Time period 1 (T2)*
B_{16}	*Deviation in Time period 1 (T3)*
B_{17}	*Deviation in Time period 1 (T4)*
B_{18}	*Deviation in Time period 1 (T5)*
B_{19}	*Deviation in Time period 1 (T6)*
B_{20}	*Deviation in Time period 1 (T7)*

The objective function for Eston Central was

$$\boldsymbol{X_{14}} - 1{,}645\boldsymbol{X_{24}}$$

Where $\boldsymbol{X_{14}}$ is the expected gross margin E[GM] and $\boldsymbol{X_{24}}$ is the standard deviation

The E[GM] equation for the model with energy cane in Eston Central was:

$$\begin{aligned}-13265{,}1X_1 - 20451{,}9X_2 - 12880X_3 - 12880X_4 - 20397X_5 - 15623X_6 - 13463.19X_7 \\ + 3428X_8 + 20793X_9 + 46888X_{10} + 3200X_{11} + 1000X_{12} + 500X_{13} - X_{14} \\ = 0\end{aligned}$$

The coefficients in the above equation for X_1 to X_7 are the different total variable costs of production for the different sugarcane cultivar enterprises while coefficients for timber and macadamia production (X_8 to X_{10}) are the enterprises' gross margin values. Coefficients for X_{11} to X_{13} are the selling prices for the products sucrose molasses and bagasse, they can be altered. A list of variables inserted in the model with energy cane for Richmond and Mid-Illovo are provided in Appendices D and E. Models for Mid-Illovo and Eston Central were run at risk aversion coefficients (θ) that correspond with the probability of achieving a favourable outcome 95% of the time while Richmond's θ corresponded with an 85% probability. Once these models representing an alternative scenario were in place, sensitivity analyses to determine how sensitive or responsive the models were to changes in bagasse prices were performed for all three representative farm models. The results arising from this analysis are outlined in Chapter 4, Section 4.2 The impact of these bagasse price changes on cane pricing were also assessed. Section 3.2.9 describes how cane prices were calculated and the results of this analysis are presented in Section 4.4.4.

3.2.9 Calculating cane prices

As highlighted in the literature review, growers are paid based on the amount of sucrose and molasses that can be recovered from their cane, the recoverable value (RV). Monitoring the trends of the cane price per ton of cane delivered is a simpler way to estimate whether profits will be realised from total tons of cane harvested. The formula below demonstrates how the cane price would be calculated if growers were to be paid for the fibre in their cane.

$$Cane\ price = X_1 P_1 + X_2 P_2 + X_3 P_3$$

Where:

X_1 - average fibre % in cane, P_1 is the price per ton of fibre
X_2 - average sucrose % in cane, P_2 is the price per ton of sucrose
X_3 - average molasses % in cane, P_3 is the price per ton of molasses

In the above equation, fibre was used instead of bagasse. The two have a direct relationship as the bagasse used in this study is assumed to have a moisture content of 50.8%. The price of cane will differ by variety and it is not possible to calculate a price for every variety. As such, to represent all three regions, calculations were done for average percentage content of fibre, sucrose and molasses per ton of conventional cane and energy cane. Table 3-17 shows the average fibre and sucrose content in energy cane. It also shows the expected bagasse and molasses likely to be produced per every 100 tons of conventional or energy cane crushed. These were extrapolated from literature and personal communication with SASRI staff. The results of these calculations are presented in the next chapter.

Table 3-17 Average % content of (wet) bagasse, sucrose and molasses per 100 tons of conventional and energy cane delivered

Cane Variety	**Expected bagasse produced (tons)**	**Corresponding fibre %**	**Sucrose %**	**Molasses produced tons/100 tons of cane delivered**
Conventional Cane	30	15	12	4
Energy cane	52	26	8	2

The next section describes how the biorefinery appended to the mill representative model was constructed to account for extraction of sucrose, molasses and bagasse in the milling process. Other fermentable sugars were not included as these are not a component of the division of proceeds. The biorefinery appended to the mill model also accounted for energy demanded by the mill, possible use of bagasse to generate electricity or methanol and sucrose for lysine or ethanol production.

3.3 Building the biorefinery appended to the mill representative (BAM) model

This study uses partial equilibrium modelling to establish mill and farm implications of developing sugarcane mills into fully fledged biorefineries. A partial equilibrium model has two main central systems; the producer system representing the supply side of the commodity in question, and a consumer system to represent the demand side (Parappurathu, 2007). The supply side in this research is characterised by three representative farms supplying sugarcane with the methodology used clearly outlined in Section 3.2. This chapter describes the construction of the biorefinery appended to the mill (BAM) representative model using linear programming (LP) modelling to represent the demand for sugarcane which the mill processes into sugar, molasses and bagasse. The mill’s demand for these by-products will be derived from the market demand for the selected biorefinery products.

3.3.1 Background

Linear programming (LP) has been widely used in operations research to solve various optimisation problems as highlighted in Chapter 2, Section 2.8. In biorefining, these include establishment of optimal processing routes, supply chain optimisation as well as minimisation of biomass transportation cost through integration with Geographical Information Systems (GIS) based decision support tools (Ubando *et al*., 2012; Zondervan *et al*., 2011; Xie *et al*., 2009;). This research builds the biorefinery appended to the mill representative model using LP modelling to simulate the milling process and millers’ biorefinery investment options. This model, like the farm models, requires the identification of activities, constraints, resources and an objective function. It is important to understand the processes that occur in a typical SA sugar mill in order to identify the various activities for inclusion in the model. In Section 3.3.2 a description of a typical SA sugar mill and milling processes under a current scenario producing sugar, other fermentable sugars, molasses and bagasse is done.

3.3.2 Description of typical South African sugar mill and milling processes

Guest *et al*. (2019) and Rein (2007) state that a typical milling process includes seven stages, namely cane preparation, sucrose extraction (diffusion), clarification and filtration, clear juice evaporation, crystallization, centrifugal crystal separation and drying of sugar crystals, supplemented by energy provison (boiler) and cooling (cooling tower) (see Figure 3 below).

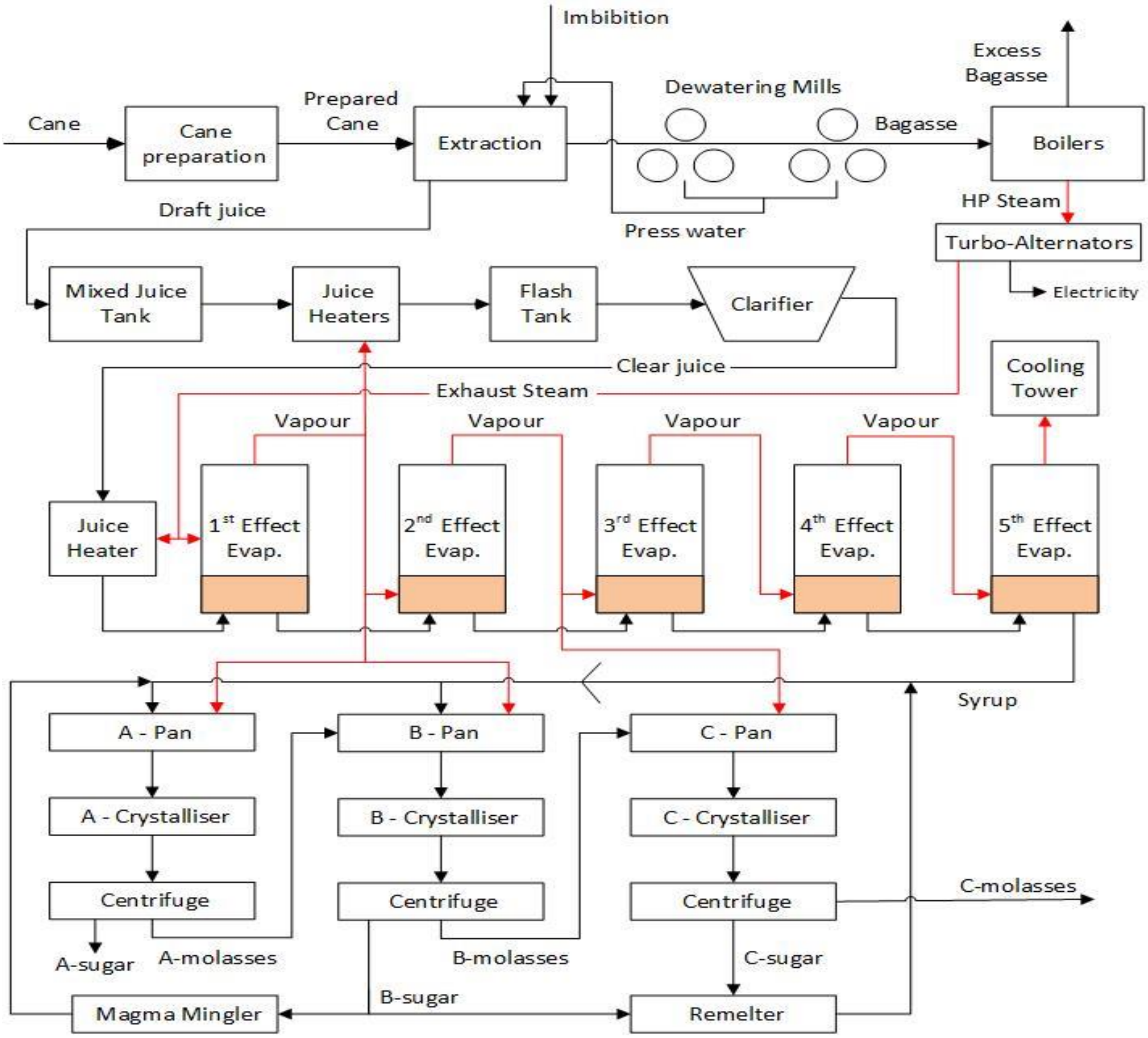


Figure 3 Flow diagram of a typical sugar mill (Guest et al., 2019)

After the cane is delivered to a mill, it is first weighed at the weighbridge and thereafter proceeds for cane preparation. At this stage, cane is cut using revolving knives, crushed with hammers and shredded by means of shredders (Rein, 2007; Smith, 1978). The main aim is to ensure that maximum sucrose extraction is achieved through rupturing as many sucrose-containing cells as possible (Kwenda, 2017; Ensinas *et al.*, 2007; Rein, 2007). Following the cane preparation stage is sucrose extraction where raw juice is separated from the fibre. Diffusers or milling tandems can be used at this stage with the main aim of separating as many solubles from the insolubles. The remaining biomass (megasse) is sent for dewatering and a small percentage of the resultant bagasse is sent to the clarifier while the rest becomes fuel in the boilers (Guest *et al.*, 2019; Rein, 2007). The greater part of a sugar mill's utilities is comprised of boilers supplying electricity and high pressure steam as well as cooling towers providing cooling water and vacuum.

Prior to the clarifier, the raw juice is heated using heaters or heat exchangers to maintain a constant juice temperature in the clarifier and eliminate any dissolved gases. After heating, the pH is neutralized using milk of lime forming a precipitate known as mud that settles at the bottom of the clarifier. The clarification process removes impurities and suspended insolubles (e.g. mud or bagasse pieces) (Rein, 2007). The clear juice is sent to the evaporation system where it is heated and concentrated from 11 °brix to about 62-68 °brix (Guest *et al.*, 2019). This stage demands high energy with most of it supplied from bagasse incineration in boilers (Jorge *et al.*, 2010; Rein, 2007). In the typical sugar mill modelled by Guest *et al.* (2019), a multiple effect (5-effect) evaporator is used for the evaporation of clear juice. This type of evaporator moderates the amount of steam required for evaporation and operates under low pressure resulting in a lower boiling point which minimises sucrose inversion. After evaporation, the crystallisation process follows.

Crystallization precipitates sucrose as sugar crystals in a series of three large pans under vacuum (A-, B- and C-pan). Temperature control is key during crystallization thus the process is done under low pressure to maintain low temperatures, avoid colour formation as well as sucrose degradation (Rein, 2007). Syrup is boiled in the A pan forming A massecuites, a thick mass of sugar crystals combined with syrup. In the centrifuges raw sugar crystals are separated from the molasses through spinning of the massecuites. The A massecuites are removed from A pans and centrifuged producing A sugar and A molasses. After centrifugation, the molasses is drained out while sugar crystals remain in the centrifuge basket and are sent for drying to increase shelf life and reduce colour formation. Molasses from the A pan is fed to the B pans which after separation form B sugar and B molasses. B molasses likewise becomes a feed for the C pans producing C sugar and C molasses. The final molasses from the C pan is the by-product of the sugar mill which can be used as cattle feed or biorefinery product production. B and C sugar are fed back to the A pan to improve sugar purity.

As part of the mill processes it is essential to understand the energy flows within mill operations. This has a bearing on changes in steam flow rates, compositions and profitability once biorefinery operations begin. From this section key activities incorporated in the model include *cane delivery, cane milling, raw juice production, bagasse fed to the boilers, clear juice production, A, B and C molasses production and lastly, sugar production.* Since the study incorporates the production of a high fibre variety, energy cane the cane delivered is split into energy cane and conventional cane. The cane crushing is therefore done for those two different types of cane. Details of the contributory factor of each of the decision variables/activities to the objective was gathered from literature and is elucidated on in Section 3.4.5.

3.3.3 The sugarcane biorefinery options in the biorefinery appended to the mill (BAM) model

As highlighted in Chapter 1, Section 1.1, a biorefinery uses biomass to produce bio-energy (power, biofuels, heat) and/or a wide range of bio-based products (chemicals and materials) (Cherubini, 2010). Nel (2010) highlights that an existing sugar mill can be successfully expanded to produce sugarcane based biorefinery products with few modifications. This is mainly due to availability of raw materials e.g. bagasse and clear juice as well as the already existing labour force, infrastructure and other utilities.

In Chapter 2 Section 2.4.2, selection of which products to include in a multiproduct biorefinery was seen to require the use of techno-economic analyses (TEA) methods that will aid in the identification of the best performing configurations economically. In South Africa, detailed TEAs are yet to be performed for many of the biorefinery products currently viewed as potentially lucrative for the South African sugarcane industry. In this study, choice of biorefinery products to include in the mill model is limited. This is mainly because apart from the study being a proof of concept, product selection was largely dependent on data availability (price, fixed and variable costs of production). Selection of the products is based on the New Product Greenhouse (NPG) toolbox (Booysen *et al.*, 2017), the Sugarcane Biorefinery Economic Analysis Toolbox (S-BEAT) (Naidoo *et al.*, 2019a) (see Section 2.4.2) and literature. Figure 4 below is a flow diagram summarising the key processes modelled in the biorefinery appended to the mill model. These include cane supply and the various feedstock that were used to produce the biorefinery products (BRFP) in the model as well as raw sugar production.

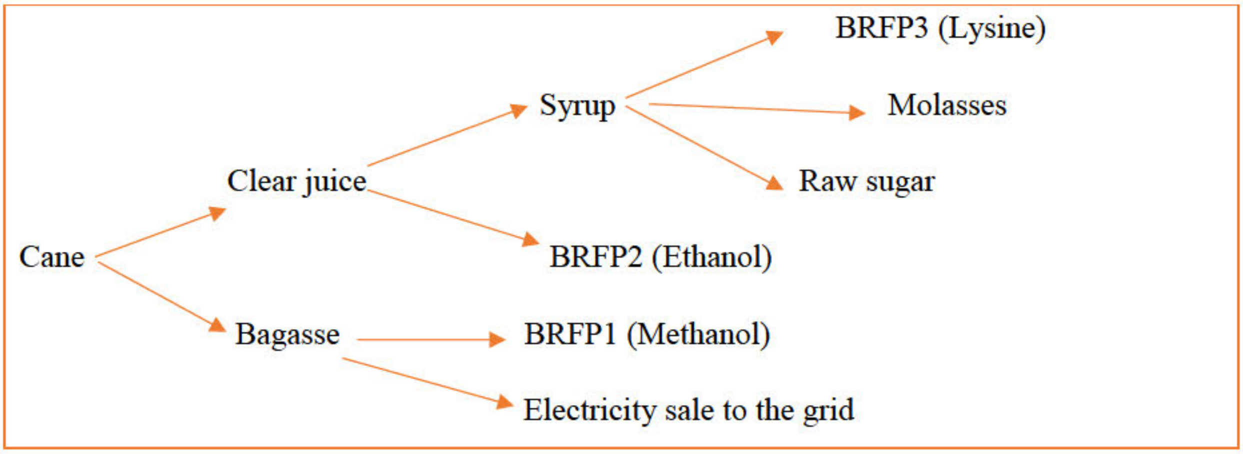


Figure 4 Flow diagram showing cane supply and the respective feedstock for selected biorefinery products

The section below describes the components of the model.

3.4 Components of the biorefinery appended to the mill (BAM) model

A linear programming model comprises of an objective reflecting the goals set by decision makers either to minimise costs or maximise profits. The objective of the BAM model is to maximise profits through an optimal selection of biorefinery products. The model has decision variables or activities used by the decision maker in order to meet the objective, and constraints which are the limited resources that the decision maker is required to operate within (Beneke and Winterboer, 1984). The objective coefficient of the decision variables indicates the contributory factor of each decision variable to resource use. In this section, details of coefficient values, activities and constraints and other relevant data required in model construction are outlined.

A set of assumptions guiding development of the mill model were made. A short background and the assumption are presented in the following section.

3.4.1 Assumptions

i. While there are a number of factors that influence energy efficiency in a mill, in this study it is assumed that the boiler design has the greatest influence. As such, the mill model presents an option of two boilers. One that is old and inefficient with low steam and pressure conditions of 18 bar 360°C and another modern design operating at 45 bar 445°C (Mbohwa, 2013). **The old boiler is assumed to be already in existence while the new boiler is not.**

ii. The Length of the Milling Season (LOMS) in South Africa ranges from 30-38 weeks (Bezuidenhout and Singels, 2007), **in the model the mill is assumed to be in operation for 36 weeks (252 days, 6 048 hours)**. This is because the biorefinery product data used in the model originated from a model assuming a 36-week long LOMS.

iii. Although the sugarcane mill receives only cane from the farm, in this study **it is assumed that the mill will receive fibre, sucrose and molasses**. In the model, the bagasse, sucrose and molasses produced in the mill cannot exceed the quantity of fibre, sucrose and molasses supplied from the farms. Other fermentable sugars are not included because they are not used as a raw material for any biorefinery product.

iv. A high ash content in cane as well as a high moisture content (more than 55%) in bagasse negatively affects bagasse combustion (Reid, 2006). **The cane quality is assumed to have low ash content with bagasse that also has a good combustion efficiency. The bagasse moisture content is assumed to be 50% (Guest, 2018) which if removed results in a remaining fibrous material (dry bagasse) referred to as fibre in the study. There is a direct relationship between fibre and wet bagasse in this study.**

v. At this point, the processing costs for high fibre cane are unknown (Diniz et al., 2019). Since the cultivar of energy cane used in this study is closer to the conventional cultivars, it is assumed that the processing costs for energy cane are similar to the costs for conventional cane.

3.4.2 Cost data

In LP programming gross earnings/gross margins are a key component that aid in the identification of optimal conditions for resource allocation (Kay *et al*., 2012). A production operation’s gross earnings are calculated by subtracting the total production cost from the total income. Price, yield and production cost data are requirements in the calculation of gross margins. Prices for each of the biorefinery products (bio-methanol, lysine, electricity, bio-ethanol and sugar) were gathered from literature. The annualised variable and fixed costs of production were acquired from the operational expenditure (OPEX) S-Beat data as well literature.

According to Peters and Timmerhaus (1991), the variable or direct production costs constitute about 60% of total product cost (TPC) while fixed costs are 10-20% of direct production costs. The variable costs include raw materials, miscellaneous materials (safety clothing, cleaning materials, pipe gaskets etc.), shipping and packaging, waste management and utilities (water, electricity and steam). Fixed costs constitute maintenance, operating labour, laboratory costs, depreciation, insurance, royalties, local tax and plant overheads. It is important to note that apportionment of the above costs depends on the company's accounting methods. In this study, however, the annualised costs were readily available from S-Beat data and literature. Table 3-18 shows the annualised fixed and variable costs per ton of product produced for each of the products and the source from which the figures were obtained.

Table 3-18 Annualised fixed and variable costs for selected biorefinery products

Product	**Fixed costs (Rands)**	**Variable costs per ton of product (Rands)**	**Literature Source**
Bio-Methanol	12 400 0000	1 490	Gorgens *et al*., 2015
Bio-ethanol	173 247 645	5 230	Naidoo *et al*., 2019a, b, Step Bio briefing notes
Lysine	167 670 000	6 770	Naidoo *et al*., 2019a, b, Step Bio briefing notes

The cost of investing in a new boiler was benchmarked against the price of a modern more efficient boiler that was purchased for the Ubombo mill in Swaziland at an estimated cost of R150 million in 2014 (Phillips, 2014). The real value of the boiler in ZAR2020 was compounded using an average interest rate of 9% from 2014. The new boiler was estimated to have an investment cost of R298 million.

3.4.3 Product capacity and material flow quantities

The product and raw material capacity data of all the biorefinery scenarios except methanol was obtained from S-BEAT data. Methanol data was gathered from literature. The flow of the raw materials and corresponding product yield data was gathered from literature and S-BEAT. Table 3-19 shows the product capacity and production yield data incorporated in the model for each of the biorefinery products.

Table 3-19 Raw material capacity and production yield data

Product	Plant raw material capacity (tons)	Yield per ton of raw material (tons)	Literature Source
Bio-Methanol	255 528	0,312	Gorgens *et al*., 2015
Bio-ethanol	102 854	0,483	Naidoo *et al*., 2019a, b, Step Bio briefing notes
Lysine	180 503	0,376	Naidoo *et al*., 2019a, b, Step Bio briefing notes

3.4.4 Overview of activities/decision variables in the BAM model

Decision variables or activities are what the decision maker controls in order to meet the objective. Choice of activities for the BAM model were partly selected from key processes identified from Section 3.3.2. Table 3-20 shows all the activities incorporated in the BAM model. The objective of the model is to maximise profits through an optimal selection of selected biorefinery products.

Some decision variables/activities had to be constrained to integer values in the model. This was to allow for the modelling of yes and no decisions or discrete choices in the mill model. Such activities included boiler choice and biorefinery investment decisions which were expressed as binary integers in solving the model. These enter the solution at a level of one or zero demonstrating that the fixed costs are either fully incurred or not. The quantities of sugar and biorefinery products produced were converted to millions as this made the numbers manageable.

Table 3-20 A list of all activities incorporated in the BAM model

Activities (let X_i denote an activity)	
Index	**Definition**
X_1	*Total (tons) sugarcane conventional cane (CC) supplied*
X_2	*Total (tons) sugarcane energy cane (EC) supplied*
X_3	*Total bagasse (fibre) tons CC supplied*
X_4	*Total bagasse (fibre) tons EC supplied*
X_5	*Total sucrose tons CC supplied*
X_6	*Total sucrose tons EC supplied*
X_7	*Total molasses tons CC supplied*

X_8	*Total molasses tons EC supplied*
X_9	*Total tons Conventional Cane (CC) crushing*
X_{10}	*Total tons Energy Cane (CC) crushing*
X_{11}	*EC+CC crushing tons*
X_{12}	*EC bagasse (fibre) tons in the mill*
X_{13}	*CC bagasse (fibre) tons in the mill*
X_{14}	*Total bagasse tons EC+CC*
X_{15}	*Total EC molasses tons in the mill*
X_{16}	*Total CC molasses tons in the mill*
X_{17}	*Total tons EC+CC molasses*
X_{18}	*Total EC sucrose tons in the mill*
X_{19}	*Total CC sucrose tons in the mill*
X_{20}	*Total tons EC+CC sucrose in the mill*
X_{21}	*Total tons bagasse to boiler A*
X_{22}	*Integer (INT) boiler A*
X_{23}	*Total tons bagasse to boiler B*
X_{24}	*INT boiler B*
X_{25}	*Total electricity KWh produced from total cane crushed*
X_{26}	*Surplus Electricity KWh*
X_{27}	*Excess tons of bagasse*
X_{28}	*Storage of bagasse in tons*
X_{29}	*INT BRFP 1/Methanol investment*
X_{30}	*Total bagasse to BRFP 1 production*
X_{31}	*BRFP 1 quantity sold in tons*
X_{32}	*BRFP1 produced in millions*
X_{33}	*INT BRFP 2/ Bio-ethanol investment*
X_{34}	*EC+CC Clear juice (CJ) tons*
X_{35}	*CJ tons to BRFP2/Bio-ethanol production*
X_{36}	*BFRP 2 quantity sold in tons*
X_{37}	*BRFP2 produced in millions*
X_{38}	*CJ tons to evaporating pan*
X_{39}	*INT BRF3/Lysine investment*
X_{40}	*Total tons syrup produced*
X_{41}	*Syrup tons to BRFP3 production*
X_{42}	*BRFP3 quantity sold in tons*
X_{43}	*BRFP3 produced in millions*

X_{44}	*Syrup tons to A Sugar & Amol*
$\mathbf{X_{45}}$	*Total tons molasses produced*
X_{46}	*Total tons sugar produced*
$\mathbf{X_{47}}$	*Total Sugar quantity produced*
$\mathbf{X_{48}}$	*Sugar produced in millions*

3.4.5 Constraints and transfer rows

Similar to the components of a farm representative model in Section 3.2, a list of constraints was included in the mill representative model. Constraints are the limited resources that the decision maker is required to operate within (Beneke and Winterboer, 1984). In the BAM model, the miller is limited by the quantity of cane supplied to the mill, the different capacities of the boilers and biorefinery plant capacities. Since the BAM model receives cane from the farm representative models, the maximum cane crushed at the mill is depended on the cane supplied. Boiler and biorefinery plant capacities were obtained from literature and S-Beat data.

A number of transfer rows illustrating how the output or service of one activity can be shifted to a different activity were incorporated in the model (Beneke and Winterboer, 1984). In this case the BAM model shows transfer of bagasse into the boiler or bio-methanol production, clear juice to syrup or bio-ethanol production, syrup into molasses and sugar or lysine production. The model draws on the important processes of sugar production highlighted in Section 3.3.2 to incorporate transfer rows. Table 3-21 below shows a list of all the constraints and transfers included in the model together with corresponding linear equations.

Table 3-21 Summary of identified constraints and definitions with corresponding linear equations as they were incorporated in the mill model for Eston

List of constraints (let *B*i denote a constraint)		
Index	Definition	Corresponding equation
Resource constraints/transfer rows		
B_1	*CC supplied*	$-X_1 + X_9 \leq 0$
B_2	*EC supplied*	$-X_2 + X_{10} \leq 0$
B_3	*Total tons of CC bagasse (fibre) supplied*	$-X_3 + X_{13} \leq 0$
B_4	*Total tons of EC bagasse (fibre) supplied*	$-X_4 + X_{12} \leq 0$
B_5	*Total tons CC sucrose supplied*	$-X_5 + X_{18} \leq 0$

B_{6}	*Total tons EC sucrose supplied*	$-X_6 + X_{19} \leq 0$
B_{7}	*Total tons CC molasses supplied*	$-X_7 + X_{16} \leq 0$
B_{8}	*Total tons EC molasses supplied*	$-X_8 + X_{15} \leq 0$
B_{9}	*Total cane crushing EC+CC tons*	$-X_{10} - X_9 + X_{11} = 0$
B_{10}	*Total bagasse EC+CC tons supplied*	$-X_{12} - X_{13} + X_{14} = 0$
B_{11}	*Total CC+EC sucrose tons supplied*	$-X_{19} + X_{18} + X_{20} = 0$
B_{12}	*Total CC+EC molasses tons supplied*	$-X_{16} - X_{15} + X_{17} = 0$
B_{13}	*Bagasse to the boiler*	$-X_{14} + X_{21} + X_{23} \leq 0$
B_{14}	*Boiler A*	$-X_{21} + 284\ 256X_{22} \geq 0$
B_{15}	*Boiler B*	$-X_{23} + 300\ 000X_{24} \geq 0$
B_{16}	*Boiler choice*	$X_{22} + X_{24} \leq 1$
B_{17}	*Electricity supply Boiler (KWh)*	$-240X_{21} - 333X_{23} + X_{25} \leq 0$
B_{18}	*Electricity demand (tons) (KWh)*	$-32X_{11} + X_{25} - X_{26} = 0$
B_{19}	*Excess bagasse*	$X_{14} - X_{21} - X_{23} - X_{27} - X_{30} \leq 0$
B_{20}	*Excess bagasse transfer*	$-X_{27} + X_{28} + X_{30} \leq 0$
B_{21}	*BRFP1 capacity*	$255\ 528X_{29} - X_{30} \geq 0$
B_{22}	*BRFP1 produced/ton raw material (r.m)*	$-0.312X_{30} + X_{31} = 0$
B_{23}	*BRFP1 conversion factor*	$-X_{31} + 1\ 000\ 000X_{32} \leq 0$
B_{24}	*Total clear juice tons in the mill*	$-1.25X_{20} + X_{34} \leq 0$
B_{25}	*Clear juice tons transfer*	$-X_{34} + X_{35} + X_{38} \leq 0$
B_{26}	*BRFP2 capacity*	$102\ 854X_{39} - X_{35} \geq 0$
B_{27}	*BRFP 2 produced/ton r.m*	$-0.483X_{35} + X_{36} = 0$
B_{28}	*BRFP2 conversion factor*	$-X_{36} + 1\ 000\ 000X_{37} \leq 0$
B_{29}	*Syrup transfer*	$-0.8X_{38} + X_{40} \leq 0$
B_{30}	*Syrup to molasses and sugar*	$-X_{40} + X_{41} + X_{44} \leq 0$
B_{31}	*Tons molasses produced in mill*	$-0.3X_{44} + X_{45} \leq 0$
B_{32}	*Total tons molasses produced in mill vs tons supplied*	$X_{17} - X_{45} \leq 0$
B_{33}	*BRFP3capacity*	$180\ 503X_{39} - X_{41} \geq 0$
B_{34}	*BRFP3 produced/ton r.m*	$0.376X_{41} + X_{42} = 0$
B_{35}	*BRFP3 conversion factor*	$-X_{42} + 1\ 000\ 000X_{43} \leq 0$
B_{36}	*Tons sugar from syrup*	$-0.7X_{44} + X_{46} = 0$
B_{37}	*Total sugar produced*	$-X_{46} + X_{47} \leq 0$

B38	*Sugar conversion factor*	$X_{47} + 1\ 000\ 000X_{48} \leq 0$

Coefficient values for each of the decision variables were gathered from literature, Appendix N shows the complete matrix of the activities and constraints as they appeared in the model. In order for the partial equilibrium model to simulate market equilibrium, it was necessary to integrate the demand for sugar and the selected biorefinery products into the BAM model. The section below describes how demand was incorporated in the BAM model.

3.5 Modelling market demand for selected biorefinery products

The complete partial equilibrium model will be optimised using a scenario which maximises the gross earnings by the industry for the purposes of DOP thus simulating a heavily regulated industry scenario. The researcher intends to determine the optimal quantities and market prices of the selected biorefining products through model optimisation. Establishing the prices and quantities of these products requires market demand and price information to be included in the model.

The quantity demanded for a commodity is a function of a number of factors that include price of the commodity and that of substitutes, income of buyers, and consumer taste among other factors. In this section of the model, focus was on the interaction of product price and the demand for the product. As such, demand functions were calculated for each of the products, sugar, lysine, bio-ethanol and bio-methanol. A demand function can be defined as a mathematical equation expressing the relationship between the product price and quantity demanded for the product. The demand function is calculated by the formula

$$P = a + bQ$$

Where P is the price,
a is represents the y/x intercept or the price at which no product sells
b is the slope calculated using the formula $\Delta P/\Delta Q$ and,
Q is the quantity demanded

The market equilibrium model can only be constructed when the above parameters are known. Hazel and Norton (1986) state that the initial (base-year) price of product, the own price elasticity of demand and the initial quantity demanded are three prerequisites for building the demand side of the model. In order to calculate these parameters, it was necessary to establish the current quantity demanded, current price and price elasticity of demand for each of the products. The price elasticity of demand, defined as the measure of the responsiveness or sensitivity of a product's quantity demanded to a change in its price is calculated by the formula;

$$\eta = \left(\frac{\Delta Q}{\Delta P}\right)\left(\frac{P}{Q}\right)$$

The section below describes the market data used for building the demand section of the model and demonstrates how the parameters were calculated. Assumptions made for the data that was unavailable in literature are also outlined.

3.5.1 Current prices, quantity demanded, price elasticity of demand for each of the products

In this section, the assumptions, estimated market size, current price and current quantity demanded (both local and export demand) of sugar and the selected biorefinery products are presented in tabular form. Selling prices of each biorefinery product per unit were gathered from literature and included in the model. Following every table are calculations of demand functions for each of the products.

Table 3-22 Assumptions and market information for raw sugar

Sugar	
Assumptions	The quantity consumed locally is the equilibrium quantity when demand is equals to supply in the market
Estimated Market size	Out of 2 227 248 tons of sugar produced in 2019/20, 1 249 476 tons were sold locally and 967 579 tons were exported (SACGA, 2020)
Current Demand	Local demand- 1 249 476 tons (1.25 millions of tons) Export demand- 967 579 tons
Current price per ton	R9 785
Price elasticity of demand	-0,5 (Cleasby, 1991; Oosthuizen, 1980)

To calculate the sugar demand function, the elasticity of demand (η) was set at -0.5 as indicated in Table 3-22. Calculations were as below

Demand function equation: $P = a + bQ$

To the calculate the b coefficient, formula is: $\Delta P / \Delta Q$

Elasticity of demand (η): $\left(\frac{\Delta Q}{\Delta P}\right)\left(\frac{P}{Q}\right)$

Therefore, using the elasticity of demand formula, b is: $\frac{P}{Q}/\eta$

$$b = \frac{9\,785}{1{,}25}/-0{,}5$$

b = - 15 656

To get the a coefficient b is substituted into the demand function equation.

$$9\,785 = a - 15\,656(1{,}25)$$

$$a = 29\,355$$

Substituting a and b coefficients in the demand function equation;

$$\therefore \qquad \boldsymbol{P = 29\,355 - 15\,656\,(Q)}$$

Estimates of possible demand quantities also referred to as estimates or alternative choices were done and included in the model as activities. These were used to calculate corresponding prices for each choice/segment. Further explanation to this is highlighted in Section 3.5.2.

Table 3-23 Assumptions and market information for bio-methanol

Bio-methanol	
Assumptions	• Synthetic methanol and bio-methanol are close substitutes • The quantity consumed is the equilibrium quantity when demand is equals to supply in the market • The demand for bio-methanol is a fraction of the mandatory blending regulations of 5% biodiesel into mineral diesel, also bearing in mind that 200ml of methanol is used to make 1 litre of biodiesel (Cambray, 2007) • The methanol price is linked to the diesel price in South Africa since both are fuels • The elasticity of demand is linked to that of diesel
Estimated Market size	With the country's demand exceeding the domestic supply, the excess demand was met by imports. Diesel was the most imported fuel, from 2,6 billion litres in 2009 to 6 billion in 2018 following an increased use of diesel in both the commercial and retail sectors (Department of mineral resources and energy, 2021)
Current Demand	140 000 (0.14 millions of tons)
Current price per ton	R6 300
Price elasticity of demand	-0,2 (Boshoff, 2011)

Elasticity of demand (η): $\left(\frac{\Delta Q}{\Delta P}\right)\left(\frac{P}{Q}\right)$

Therefore, using the elasticity of demand formula, b is: $\frac{P}{Q}/\eta$

$$b = \frac{6\ 300}{0{,}14}/-0.2$$

b = - 225 000

To get the a coefficient b is substituted into the demand function equation.

$$6\ 300 = a - 225\ 000(0{,}14)$$

$$a = 37\ 800$$

Substituting a and b coefficients in the demand function equation;

$$\therefore \qquad \boldsymbol{P = 37\ 800 - 225\ 000\ (Q)}$$

Table 3-24 Assumptions and market information for bio-ethanol

Bio-ethanol	
Assumptions	• Synthetic ethanol and bio-ethanol are close substitutes • The quantity consumed is the equilibrium quantity when demand is equals to supply in the market, • The bio-ethanol price is linked to the petrol price in South Africa since both are fuels • The demand for bio-ethanol is a fraction of the mandatory blending regulations of 2% bio-ethanol into petrol • The price elasticity of demand is linked to that of petrol
Market size	About 36% of the demand is met by synthetic fuels (synfuels), which are produced locally, largely from coal and from natural gas. Products refined locally from imported crude oil meet the remaining 64% (Department of mineral resources and energy, 2021)
Current Demand	120 000 (0.12 million tons)
Current price per ton	R9 000
Price elasticity of demand	-0.4 (Boshoff, 2011)

Elasticity of demand (η): $\left(\frac{\Delta Q}{\Delta P}\right)\left(\frac{P}{Q}\right)$

Therefore, using the elasticity of demand formula, b is: $\frac{P}{Q}/\eta$

$b = \frac{9\ 000}{0{,}12}/{-0{,}4}$

b = - 187 500

To get the a coefficient b is substituted into the demand function equation.

$$9\ 000 = a - 187\ 500(0{,}12)$$

$$a = 31\ 500$$

Substituting a and b coefficients in the demand function equation;

$\therefore$ $$\boldsymbol{P = 31\ 500 - 187\ 500\ (Q)}$$

Table 3-25 Assumptions and market information for lysine

Lysine	
Assumptions	• The quantity consumed is the equilibrium quantity when demand is equals to supply in the market, • The demand is derived from the quantity of lysine imported • The price elasticity of demand is linked to that of one of its end uses, animal feed
Market size	The lysine imports exceed by far the lysine exports (Department of mineral resources and energy, 2021)
Current Demand	250 000 (0.25 millions of tons)
Current price per ton	R20 000
Price elasticity of demand	-0,7 (Richardson and Ray, 1978)

Since most lysine is imported there was no need to calculate the demand function for this product. The price for lysine is exogenously determined, or would be set by the current import price for the commodity.

The electricity price was set between R344,25 and R617,70 per MWh produced based on the lowest and highest fully indexed tariffs for the Renewable Energy IPP Procurement Programme (REIPPPP) for wind and solar energy produced, respectively (IPP Renewables, 2021).

3.5.2 Demand segments, corresponding prices and revenue data

As highlighted earlier at the beginning of Section 3.5, the model when optimised, selects an optimal price and quantity for raw sugar and the biorefinery products. The base demand or current demand for each of the products is used as a starting point for additional demand estimations or alternative choices that can be selected by the model (Hazel and Norton, 1986). These estimates labelled D_1, D_2 etc are located along the demand function. They are used to calculate corresponding prices for the products labelled $P_{1,}$ $P_{2,}$ etc.

Figure 5 below graphically shows where the demand estimates and corresponding market prices appear along a demand function. The demand estimates and prices are included in the model as various segments (labelled S1, S2, S3 etc).

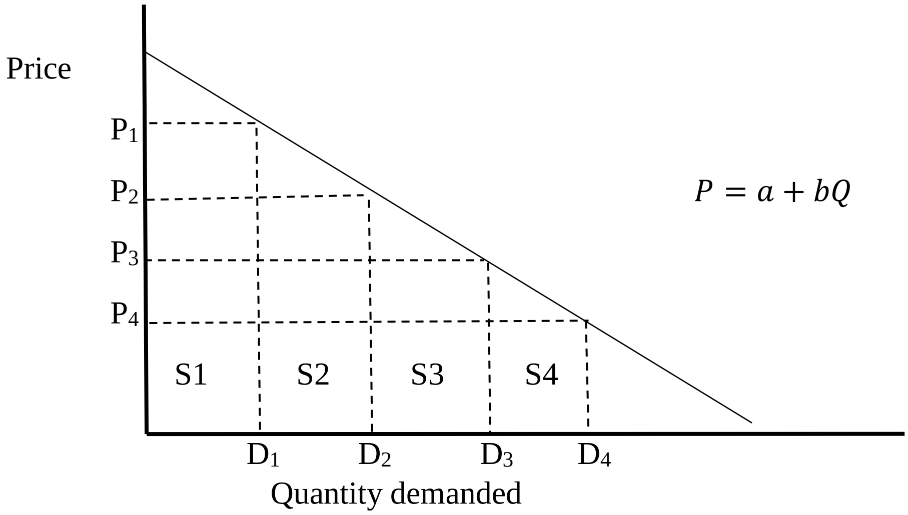


Figure 5 A graphical representation of a demand function and the possible price and quantity options

Each of the products except lysine, had five segments or alternative choices of price and demand from which an optimal solution would be drawn. Tables below illustrate the demand estimates for each of the products and their corresponding prices. An additional segment for sugar export was included. The quantity of sugar exported by the Eston mill for the year 2019/20 was included in the model.

It is important at this stage to note that since the BAM model's focus is on one cane supply area, the demand information inputted into the model had to be adjusted for a single mill. This was done by using the current demand as the base (D_0) and subtracting D_0 from D_1 and D_2 etc. The mill's demand for each of the products and all segments was multiplied with the price to calculate the expected revenue for each segment. This revenue was included in the objective function. An example of a mini-tableau of this as it appears in excel is demonstrated in Tables 3-26 to 3-29.

Table 3-26 Sugar segments and corresponding prices and revenue

Sugar					
Segment	**1**	**2**	**3**	**4**	**5**
Quantity demanded (tons)	1 300 000	1 320 000	1 350 000	1 380 000	1 400 000
Quantity demanded (D_X, millions of tons)	1,30	1,32	1,35	1,38	1,40
Corresponding equilibrium price (R/t)	9002	8689	8219	7749	7436
***1,25 (D_0)**	0,05	0,07	0,10	0,13	0,15
****Total Revenue (million rands)**	450,1	608,23	821,9	1007,37	1115,4
Export tons 2020	40 000	0,04			
Export price	5000	200,00			

*This row adjusts the demand for one mill using the formula **(D_X-D_0)**

** The revenue is calculated by multiplying the price and the adjusted demand for each segment

Table 3-27 Bio-ethanol segments and corresponding prices and revenue

Bio-ethanol					
Segment	**1**	**2**	**3**	**4**	**5**
Quantity demanded (tons)	135 000	140 000	150 000	160 000	165 000
Quantity demanded (millions of tons) (D_X)	0,135	0,14	0,15	0,16	0,165
Corresponding equilibrium price (R/t)	7125	6188	5250	3375	1500
***0,12 (D_0)**	0,015	0,02	0,03	0,04	0,045
****Total Revenue (million rands)**	107	124	158	135	68

*This row adjusts the demand for one mill using the formula **(D_X-D_0)**

** The revenue is calculated by multiplying the price and the adjusted demand for each segment

Table 3-28 Bio-methanol segments and corresponding prices and revenue

Bio-methanol					
Segment	**1**	**2**	**3**	**4**	**5**
Quantity demanded (tons)	150 000	155 000	158 000	160 000	165 000
Quantity demanded (million tons) (D_X)	0,15	0,155	0,158	0,16	0,165
Corresponding equilibrium price (R/t)	5175	4050	2925	2250	675
***0,14 (D_0)**	0,01	0,015	0,018	0,02	0,025
****Total Revenue (million rands)**	51,75	60,75	52,65	45	16,875

*This row adjusts the demand for one mill using the formula **(D_X-D_0)**

** The revenue is calculated by multiplying the price and the adjusted demand for each segment

Table 3-29 Lysine segment and corresponding prices and revenue

Lysine	
Segment	**1**
Quantity demanded (tons)	315 000
Quantity demanded (million tons) (D_X)	0,315
Corresponding price (R/t)	17 714
***0,25 (D_0)**	0,065
****Total Revenue (million rands)**	1 950

*This row adjusts the demand for one mill using the formula **(D_X-D_0)**

** The revenue is calculated by multiplying the price and the adjusted demand for each segment

3.5.3 Incorporating demand data into the model

All the demand segments are added as activities in the model. The model should select one of the activities as an optimal solution. A constraint known as the convex combination constraint (CCC), that limits the choice of a segment to one is added in the model. Table 3-30 demonstrates a mini-tableau for sugar segments.

Table 3-30 A mini-tableau showing sugar segments and the convex combination constraint (please refer to Appendix N to view the rest of the components of the BAM model)

		Domestic demand sugar segments							
	Sugar millions	1	2	3	4	5	Exports	RHS	
Supply & Demand for sugar	-1	0,05	0,07	0,10	0,13	0,15	0,04	≤	0
Domestic CCC		1	1	1	1	1		≤	1
Objective function		450,10	608,20	821,90	1007,40	1115,40	250,00		Max

In order to verify functionality of the BAM model it was necessary to combine it with the farm models which supply raw materials. The section below describes how the two models were merged.

3.6 Combining the farm and BAM models

Merging the three farm representative models with the BAM model involved summing up and separating all quantities of sucrose, bagasse (fibre), molasses from conventional and energy cane. This allowed for easier analysis of the current scenario (with conventional cane only) and a scenario in which energy cane is included in the model.

Initially, there was no separation of the type of cane from which sucrose, molasses or bagasse emanated from. It became necessary to make this demarcation when combining the models for easy analysis after integrating the models. The transfer rows in the models for sucrose, molasses and bagasse were expanded to differentiate sucrose, molasses and bagasse arising from conventional or energy cane (Table 3-31). The same was done for Mid-Illovo and Richmond, additional transfer activities for these areas are shown in Appendix F. Table 3-32 and Table 3-33 demonstrate how the selling activities and summation of sucrose, molasses and bagasse were integrated into the model.

Table 3-31 Mini tableau of additional transfer rows separating cane products from conventional cane and energy cane for Eston Central (please refer to Appendix N to view the rest of the components of the BAM model)

	MPN12 ha	MP Energy Cane- ha	MPN31 ha	FSN31 ha	FSN54 ha	FCN48 ha	FCN50 ha	Sugarcane tons harvested EC	Sugarcane tons harvested CC	Sucrose CC	Sucrose EC	Molasses CC	Molasses EC	Baggase CC	Bagasse EC	RHS	
Sugarcane transfer CC (tons)	-50		-48	-50	-84	-55	-51		1							=	0
Sugarcane transfer EC (tons)		-85						1								=	0
Sucrose transfer CC (tons)	-6,50		-6,18	-6,5	-10,92	-7,15	-6,57			1						=	0
Sucrose transfer EC (tons)		-6,80									1					=	0
Molasses transfer CC (tons)	-2		-1,90	-2	-3,36	-2,20	-2,02					1				=	0
Molasses transfer EC (tons)		-0,34											1			=	0
Bagasse transfer CC (tons)	-15		-14,25	-15	-25,20	-16,50	-15,15							1		=	0
Bagasse transfer EC (tons)		-44,20													1	=	0

Table 3-32 Mini tableau of activities and constraints for conventional and energy cane products Eston Central (please refer to Appendix N to view the rest of the components of the BAM model)

ESTON CENTRAL										
	Sugarcane tons harvested EC	Sugarcane tons harvested CC	Sucrose CC tons from farms	Sucrose EC tons from farms	Molasses CC tons from farms	Molasses EC tons from farms	Bagasse CC tons from farms	Bagasse EC tons from farms	RHS	
Sum Cane Supply CC		-1							=	0
Sum Cane Supply EC	-1								=	0
Sum Sucrose Supply CC			-1						=	0
Sum Sucrose Supply EC				-1					=	0
Sum Molasses Supply CC					-1				=	0
Sum Molasses Supply EC						-1			=	0
Sum Bagasse Supply CC							-1		=	0
Sum Bagasse Supply EC								-1	=	0

Table 3-33 Mini tableau of activities and constraints for supply of bagasse, sucrose and molasses from all three representative farms (please refer to Appendix N to view the rest of the components of the BAM model)

						SUMMING SUPPLY FROM ALL THREE REPRESENTATIVE FARMS							
Total in tons	Total sugarcane CC tons harvested	Total sugarcane EC tons harvested	Total Bagasse CC tons from farms	Total Bagasse EC tons from farms	Total Sucrose CC tons to the mill	Total Sucrose EC tons to the mill	Total Molasses CC tons to the mill	Total Bagasse EC tons to the mill	CC tons supplied to the mill	EC tons supplied to the mill	CC bagasse tons to the mill	RHS	
Sum Cane Supply CC	-1								1			=	0
Sum Cane Supply EC		-1								1		=	0
Sum Sucrose Supply CC					1							=	0
Sum Sucrose Supply EC						1						=	0
Sum Molasses Supply CC							1					=	0
Sum Molasses Supply EC								1				=	0
Sum Bagasse Supply CC			-1								1	=	0
Sum Bagasse Supply EC				-1				1				=	0

The complete model had 168 activities and 150 constraints. This led to the use of a more advanced solver software, the What'sBest software by Lindo Systems which can easily solve a model of such size. A list of all activities and constraints in the merged model is illustrated in Appendices F and G.

The objective function equation for the integrated model for the Eston cane supply region was:

$$\begin{aligned} X_{31} + X_{66} + X_{103} - 298X_{127} + 0{,}00000043X_{129} - 124X_{132} - 0{,}000149X_{133} \\ - 173{,}25X_{136} - 0{,}0052303X_{138} - 167{,}67X_{142} - 0{,}006771X_{144} \\ + 450{,}1X_{152} + 608{,}23X_{153} + 821{,}95X_{154} + 1\,007{,}44{,}1X_{155} + 1\,115X_{156} \\ + 250X_{157} + 106{,}68X_{158} + 123{,}76X_{159} + 157{,}5X_{160} + 135X_{161} + 67{,}5X_{162} \\ + 51{,}75X_{163} + 60{,}75X_{164} + 52{,}65X_{165} + 45X_{166} + 16{,}89X_{167} \\ + 1151{,}4X_{168} = Maximise \end{aligned}$$

See Appendices F and G for the definition of all variables and constraints in the combined model.

4. RESULTS AND DISCUSSION

This chapter presents and discusses the results of this study. The first section illustrates the findings from data gathered for the purposes of understanding the cane supply distribution, cane and recoverable yield performance and cultivar adoption for the three regions of the Eston cane supply area. Section 4.2 shows a sensitivity analysis on bagasse price changes for the Eston Central farm representative model under two scenarios. One scenario included energy cane and the other excluded this high fibre variety. In Section 4.3 a sensitivity analysis on the complete partial equilibrium model is done for different bagasse prices. This simulates a scenario in which bagasse (representing the fibre in the cane) is included in the cane payment formula thus rewarding growers for the fibre in their cane. Implications on farm and mill investment decisions as well as the division of proceeds are outlined and discussed in this section.

4.1 Adoption and performance of cane cultivars in three regions of the Eston cane supply area[1]

Three regions in the Eston cane supply area were analysed, namely, Eston Central, Mid-Illovo and Richmond. Grower delivery data from Cane Testing Services (CTS) for the years 2011/12 to 2017/18 for a sample of 33 large scale growers was used to establish cane supply, cultivar adoption as well compare performance of different cane cultivars in the region. This data was needed in the construction of the farm representative model presented in the methodology chapter Section 3.2.

4.1.1 Cane supply distribution in the sub regions of the Eston cane supply area

In the 2017/18 season, 36 514 ha were under cane and 1 559 663 tons of cane were delivered to the mill (SACGA, 2019). CTS data for the farmers delivering to the Eston mill showed that of the three regions, Mid-Illovo has the highest number of total deliveries made per year. The years observed were from 2011/12 (labelled 2012 in the graphs) to 2017/18 (labelled 2018 in

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[3] This section gave rise to a peer reviewed and award-winning paper at the SASTA conference 2019 referenced as: Mafunga WP, Ferrer S, Botha P and Stark A. 2019a. Adoption and performance of cane cultivars in three regions of the Eston cane supply area. *Proceedings of the South African Sugar Technologists' Association,* Mount Edgecombe, Durban, South Africa 92: 86-97

the graphs) and each delivery is approximately 30 tons of sugar cane. Figures 6 to 8 illustrates this information in graphical format.

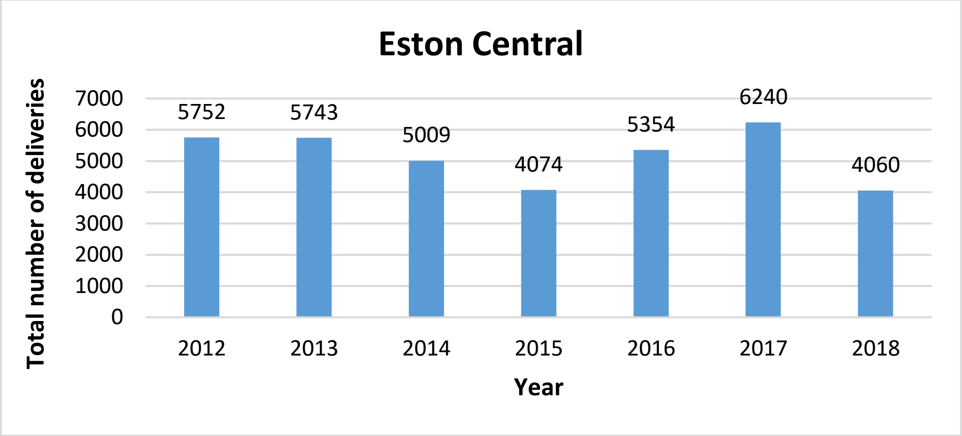

Figure 6 Total number of deliveries made in the Eston Central region for a sample of 11 large scale growers, CTS data (2018)

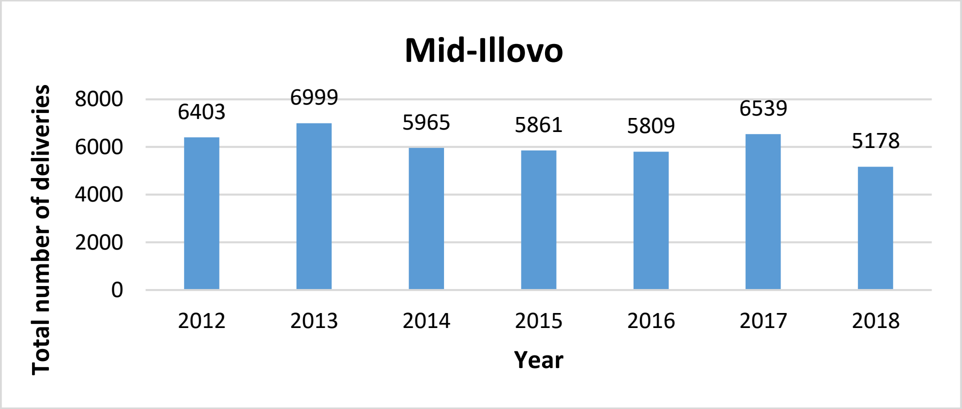

Figure 7 Total number of deliveries made in the Mid-Illovo region for a sample of 11 large scale growers, CTS data (2018)

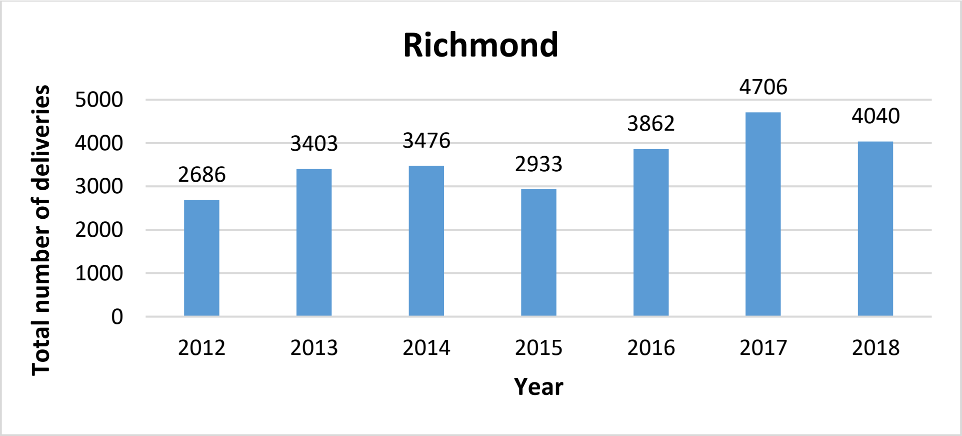

Figure 8 Total number of deliveries made in the Richmond region for a sample of 11 large scale growers, CTS data (2018)

4.1.2 Cane cultivar adoption in the Eston, Mid-Illovo and Richmond area

This section shows in tabulated form the total percentage of deliveries made by farmers to the Eston mill for each cane cultivar in each region per year from 2011/12 to 2017/18. In order to meet part of Objective One, cane cultivar adoption across all regions was identified by calculating the total number of deliveries made per cultivar for the seven years. This was expressed as a percentage of total deliveries made in that year per cultivar for the three regions (Tables 4-1 to 4-3). Please note that 2018 data is up to the month of August, and not the full 2017/18 season.

Table 4-1 A table showing cane cultivar percentage deliveries for Eston Central from 2011/12 to 2017/18

Year Cultivar	2011/12	2012/13	2013/14	2014/15	2015/16	2016/17	2017/18
N12	68,90	60,82	58,97	56,26	47,72	45,06	39,61*
N16	2,24	3,90	2,34	2,95	2,07	1,83	1,65
N31	19,32	20,58	22,00	20,08	19,33	12,82	18,20*
N35	1,48	2,59	1,46	0,69	0,75	0,72	0,10
N36	0,09	0,68	0,24	0,71	0,07	0,74	0,10
N37	5,51	4,02	3,71	5,28	2,80	4,76	2,14*
N39	0,00	1,01	0,86	0,74	0,58	0,50	0,54
N40	0,33	0,00	0,34	0,20	0,00	0,16	0,00
N41	0,30	0,31	1,90	1,62	1,85	2,26	1,16*
N46	0,00	0,00	0,00	0,34	0,00	0,00	0,00
N48	0,00	1,08	2,34	7,14	10,65	7,95	12,12*
N50	0,00	0,00	0,00	2,65	9,36	7,87	7,14*
N51	0,00	0,00	0,00	0,00	0,11	0,05	0,00
N52	0,00	0,00	0,00	0,00	2,13	6,67	3,67*
N54	0,00	0,00	0,00	0,25	1,29	5,27	7,49*
N56	0,00	0,00	0,00	0,00	0,00	0,03	0,00
Unknown	1,83	5,01	5,84	1,09	1,29	3,31	6,08

*Indicates popular varieties with above 1% delivery as of August 2018

Table 4-2 **A table showing percentage deliveries by cane cultivar for Mid-Illovo from 2011/12 to 2017/18**

Year Cultivar	2011/12	2012/13	2013/14	2014/15	2015/16	2016/17	2017/18
N12	63,42	64,92	62,36	74,92	62,70	65,42	46,49*
N16	8,30	8,84	5,70	8,04	6,89	7,98	2,39
N31	5,36	2,14	3,67	2,08	3,46	1,96	4,77*
N32	0,02	0,00	0,00	0,00	0,02	0,06	0,00
N35	0,11	0,29	0,25	0,32	0,31	0,06	0,19
N36	0,03	0,00	0,00	0,02	0,00	0,00	0,00
N37	9,89	6,79	11,01	7,71	9,09	4,68	5,79*
N39	0,00	0,17	0,77	0,10	0,10	0,00	0,29
N41	0,06	0,00	0,08	0,03	0,14	0,14	0,15
N42	0,00	0,00	0,00	0,00	0,00	0,02	0,00
N48	0,00	0,29	0,69	5,70	9,83	5,55	13,02*
N50	0,00	0,00	0,00	0,61	1,07	2,05	1,26*
N51	0,00	0,00	0,00	0,00	0,02	0,00	0,00
N52	0,00	0,00	0,00	0,00	0,21	0,32	1,51*
N54	0,00	0,00	0,00	0,02	0,79	3,41	8,48*
N56	0,00	0,00	0,00	0,00	0,00	0,02	0,00
Unknown	12,81	16,56	15,47	0,45	5,37	8,33	15,66

*Indicates popular varieties with above 1% delivery as of August 2018

Table 4-3 **A table showing percentage deliveries by cane cultivar for Richmond from 2012 to 2018**

Year Cultivar	2011/12	2012/13	2013/14	2014/15	2015/16	2016/17	2017/18
N12	44,08	43,20	33,72	34,47	20,38	27,11	13,07*
N16	0,93	0,29	0,43	0,07	0,10	0,02	0,00
N30	0,00	0,00	0,00	0,82	0,00	0,00	0,00
N31	7,82	7,05	10,85	8,32	9,87	11,16	8,66*
N35	14,52	10,11	9,12	6,38	6,21	3,00	5,94*
N36	0,82	0,00	0,86	1,94	1,66	1,59	1,19*
N37	28,97	31,50	32,94	33,55	32,03	22,18	25,59*
N39	0,00	0,68	0,23	0,24	0,70	0,59	0,10
N40	0,00	0,00	0,03	0,00	0,03	0,00	0,00
N41	1,75	4,03	5,21	2,49	4,12	1,49	5,67*
N42	0,00	0,00	0,00	0,00	0,00	0,13	0,00
N48	0,00	2,17	5,15	10,13	20,22	20,46	24,36*
N50	0,00	0,00	0,00	0,55	1,45	5,42	1,41*
N51	0,00	0,00	0,00	0,00	0,00	0,11	0,54
N52	0,00	0,00	0,00	0,00	1,14	2,21	3,64*
N54	0,00	0,00	0,00	0,31	0,83	3,53	9,18*
Unknown	1,11	0,97	1,46	0,73	1,26	1	0,65

* Indicates popular varieties with above 1% delivery as of August 2018

Out of the 68 sugarcane cultivars released since 1987 in South Africa, records show that 16 have been grown in the Eston cane supply area from 2012 to date (Mafunga *et al*., 2019a). Cultivar N12 continues to be the popular cane cultivar in Eston Central and Mid-Illovo despite a noted reduction in percentage deliveries from 2011/12 to 2017/18. The main reason for its decline as a dominant variety is the difficulty in accessing clean seed cane as the cane in the region is often infected with yellow leaf syndrome and mosaic disease. In Richmond, N12 has steadily declined for the same reason leaving N37 and N48 popular, with an average percentage delivery of approximately 25% each. Percentage deliveries for new cultivars such as N54 is increasing across all regions mainly due to high cane yields realised in an 18 month cycle. The shorter cycle allows farmers to harvest cane thrice instead of twice in four years.

4.1.3 Recoverable value (RV) and cane yield of common cane cultivars by region in the Eston cane supply area

In the sugarcane industry, growers are paid for the Recoverable Value (RV) of sugar in their cane (Groom, 1999). This refers to the value of the molasses and sugar recovered from the sugarcane delivered by an individual grower, while accounting for the fibre and non-sucrose in cane. According to Mafunga *et al*. (2019a), Mid-Illovo has the highest cane yields in all cultivars reaching a maximum of approximately 170 tons/ha for N54 in 2018. Figures 9-11 demonstrates the variability in cane tonnage per hectare harvested in each region as well as Recoverable Value (RV %) of the commonly harvested cane cultivars.

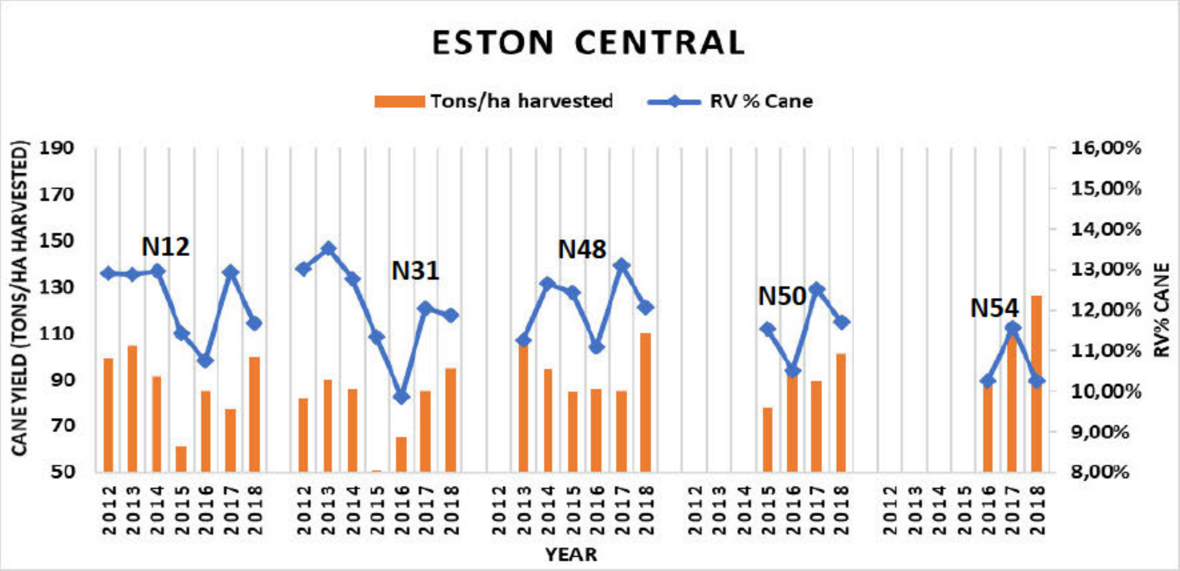

Figure 9 Graph showing cane yield and RV% cane for the 5 cultivars most harvested in the Eston Central region (Mafunga et al., 2019a).

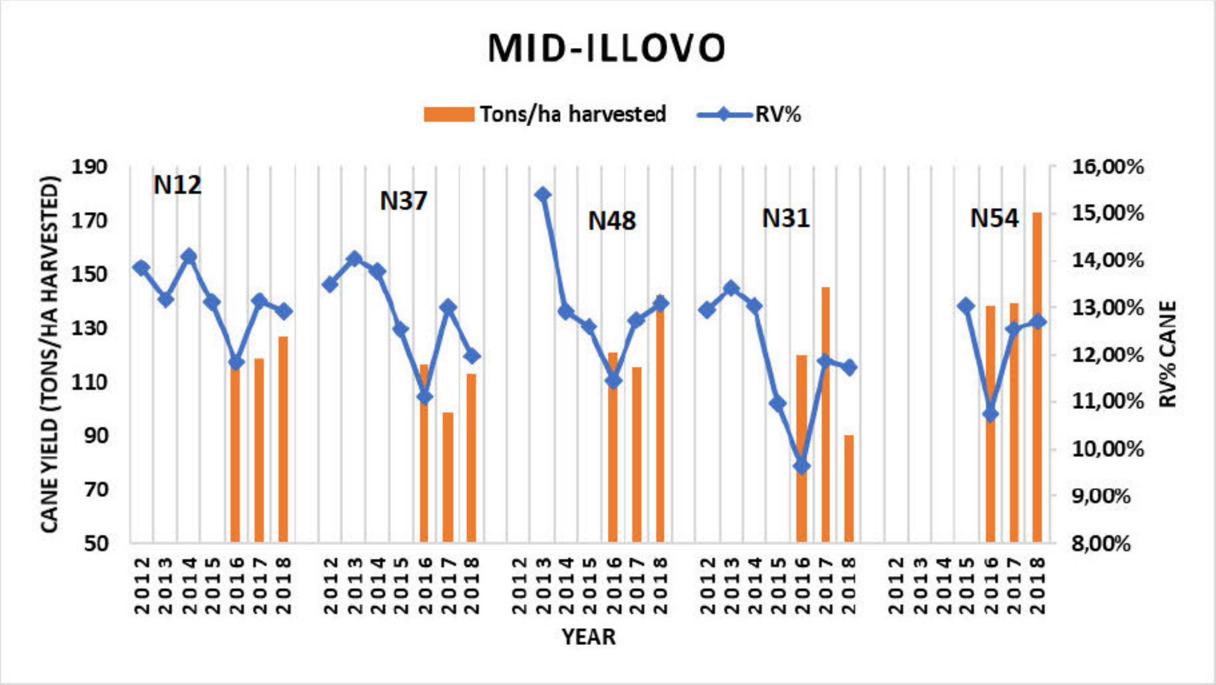

Figure 10 Graph showing cane yield and RV% cane for the 5 cultivars most harvested in the Mid-Illovo region (Mafunga et al., 2019a)

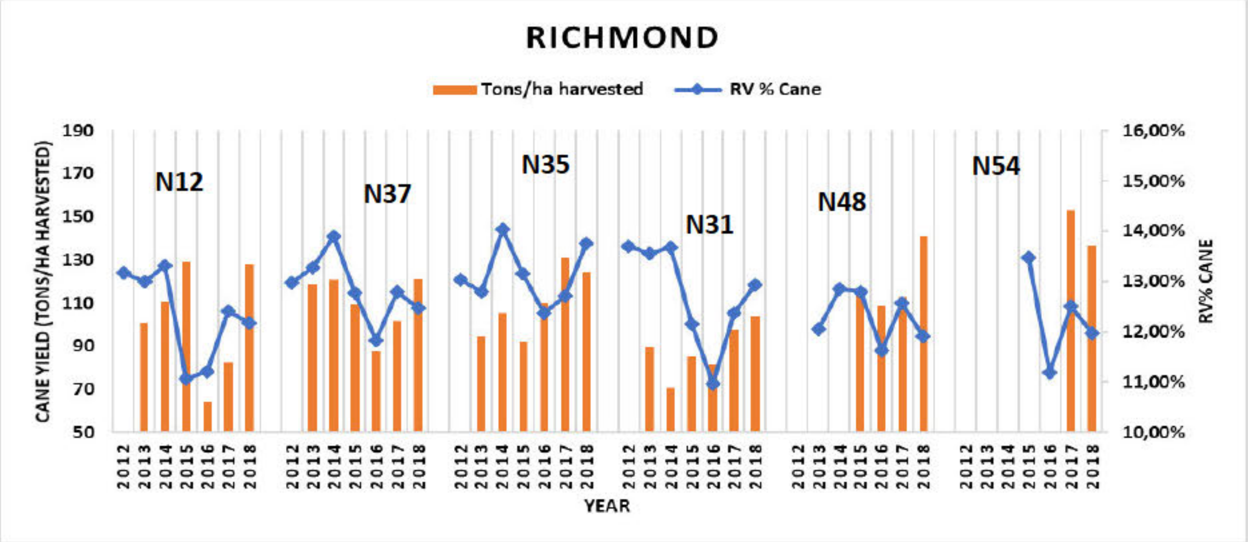

Figure 11 Graphs showing RV% and cane yield per cane cultivar for the Richmond region (Mafunga et al., 2019a).

The graphs show that varieties perform differently in terms of both RV and cane yield in the different regions depending on (among other things) weather conditions and geographical location. Drought years (2015 and 2016) in the Eston cane supply area depressed both cane tonnages and RV yields across all regions. Cultivars N12 (64 tons/ha) and N31 (51 tons/ha) had very low cane tonnage in 2015 for Richmond and Eston Central, respectively. While RV values can be as high as 15% in good rainfall years (N48, Mid-Illovo, 2014), in 2016, a drought year, the RV value for N31 was very low, at 9,6% in Mid-Illovo.

The results in this section informed the researcher on the cane varieties, cane yields and cane supply for the Eston region. This information was foundational in constructing farm representative models. In the next section, the results of the sensitivity of the Eston Central farm representative model to exogenous price changes of bagasse with and without inclusion of a high fibre cane cultivar (energy cane) are presented.

4.2 The sensitivity of growers' production decisions to changes in the bagasse price for the Eston Central region supply area[2]

A sensitivity analysis determines how responsive a model is to changes in key values, such as variable costs and product prices for a chosen farm plan (Beneke and Winterboer, 1984). This section reports results for a sensitivity analysis on bagasse price changes for the Eston Central region. Two scenarios were analysed, i.e. Scenario 1: Changes in bagasse prices without energy cane and Scenario 2: Changes in bagasse prices with energy cane. Figure 12 displays two pseudo-supply curves for the two scenarios.

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[2] This section gave rise to a peer reviewed paper at the SASTA conference 2019 referenced as: **Mafunga WP**, Ferrer S, and Stark A. 2019b. The sensitivity of growers' production decisions to changes in the bagasse price for the Eston Central region. *Proceedings of the South African Sugar Technologists' Association,* Mount Edgecombe, Durban, South Africa 92: 123-138

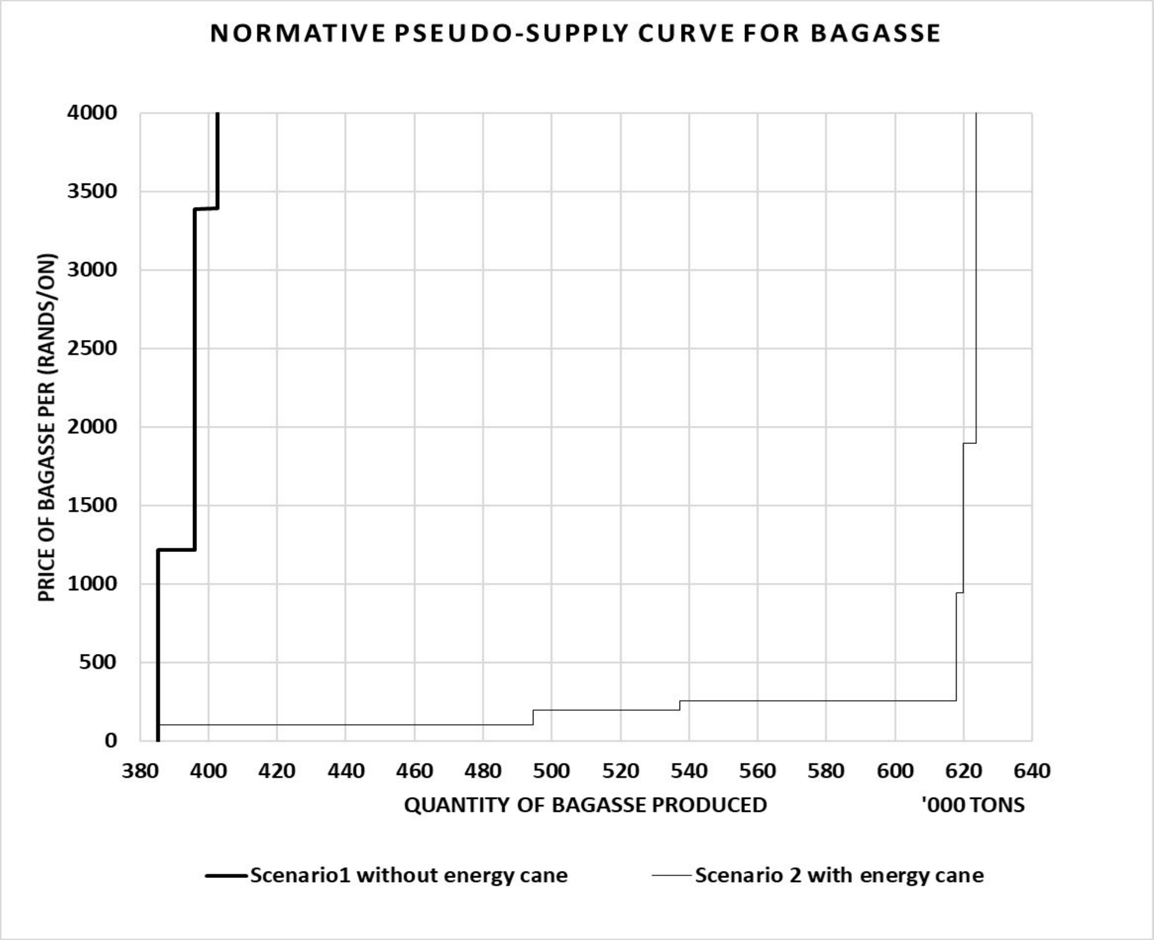

Figure 12 A normative pseudo-supply curve for bagasse under two scenarios for Eston Central.

At zero bagasse price per ton, the quantity of bagasse produced in both scenarios was roughly 385 000 tons/annum for the Eston Central Region because farmers have no incentive to produce bagasse-rich energy cane cultivars. As the price increased, the supply curve without energy cane was relatively insensitive to bagasse price changes compared to the supply curve with energy cane (Figure 12). In Scenario 1, even at a price of R1 500 per ton of bagasse over and above payment for sucrose and molasses, the quantity of bagasse supplied increases by less than 5%. By contrast, in Scenario 2, a price of R258 per ton of bagasse gives rise to a 60% increase in the quantity of bagasse supplied. Pseudo-supply curves for Mid-Illovo and Richmond regions were constructed and are presented in Appendix H. The supply curves display a similar trend of insensitivity to bagasse price changes under a scenario without energy cane.

The changes in quantities of bagasse delivered at different bagasse price levels was compared to the sucrose and molasses delivered to the mill at similar prices for the two scenarios. The results are presented in Table 4-4 for Eston Central. Tables for Mid-Illovo and Richmond are in Appendix K.

Table 4-4 Changes in sucrose, molasses and bagasse (fibre) quantities delivered to the mill at different bagasse price levels per ton for S1 and S2.

Eston Central	**Quantities delivered in tons**		
Bagasse Price	**Sucrose**	**Molasses**	**Bagasse**
Scenario 1 (without energy cane)			
0	166 904	51 355	385 162
1218	171 636	52 811	396 084
3390	174 522	53 699	402 744
4000	174 522	53 699	402 744
Scenario 2 (with energy cane)			
0	166 904	51 355	385 162
101	171 954	46 905	494 490
198	173 936	45 159	537 393
258	176 670	41 447	617 788
946	177 210	41 570	619 733
1899	178 252	41 807	623 492
2000	178 252	41 807	623 492
3000	178 252	41 807	623 492

The first change in the quantity of bagasse supplied is realised at R1 218 per ton for Scenario 1 (S1) where 396 084 tons/annum are produced. The first change in quantity supplied in Scenario 2 (S2) is noted at R101 per ton with production of 494 490 tons of bagasse (Figure 12). This is attributed to the increased adoption of energy cane in S2 which produces higher quantities of bagasse per ton of sugarcane crushed compared to conventional cane. The maximum price beyond which no changes in bagasse quantities are realised for S1 is R3 390 at 402 744 tons while for S2 it is R1 899 at 623 492 tons.

An analysis of the percentage increase in sucrose and molasses production from the point when the bagasse price is zero to the highest price based on the results in Table 4-4 was done. A 4,6%

and 6,8% increase in the quantity of sucrose produced for a scenario without and with energy cane respectively is noted. While expectation was that sucrose quantities would decline as growers shift to high fibre yielding varieties with increased bagasse prices, in this case there is a very slight increase. This is because, despite the fact that the type of energy cane used in this study has low sucrose levels of roughly 8% compared to conventional cane with about 12% sucrose, the high yields realised from energy cane elevate the sucrose yields. Moreover, only 33% of the land was under energy cane in accordance with the South African Sugar Research Institute (SASRI) rule stating that no more than a third of the area should be under one cultivar. This limited the extent to which energy cane could be grown and as a result, sucrose supply remains high.

Molasses deliveries declined in a scenario with energy cane by 18% (Table 4-4) mostly because the expected molasses per ton of cane crushed is very low for energy cane at 0.04% compared to 4% for conventional cane. This observation suggests that the type of energy cane grown should be carefully selected depending on the targeted end products in the biorefinery. Where more bagasse is required as a feedstock for selected biorefinery products it may be worth including energy cane varieties with even lower sucrose content. In this case, it is still possible to produce the same quantities of sugar with the variety of energy cane incorporated in the model. However, molasses levels will decline and they may be need to reconsider biorefinery products that use molasses as a raw material. The results for Richmond and Mid-Illovo show a similar trend only that for Mid-Illovo, due to its very high cane yields, the quantity of molasses delivered at different bagasse prices remained more or less constant (see Appendix K).

4.2.1 Changes in cane variety selection and enterprise selection

As the price for bagasse altered for both scenarios, the model also showed variations in enterprise selection and cane varieties grown. These results are illustrated in Table 4-5. Table 4-5 shows that in Scenario 1, the area under N12 and N48 increases as the price of bagasse increases.

Table 4-5 Distribution of area under cane and opportunity cost of land at different bagasse prices per ton for S1 and S2.

Bagasse price (Rands)	**Percentage area planted in hectares out of total arable land**					
	MP[a] N12	**MPEnergy cane**	**MP N31**	**FC[b] N48**	**FS[c] N54**	**FC Mac[d]**
Scenario 1 (without energy cane)						
0	31,46	0,00	21,97	15,30	26,61	4,66
1218	32,42	0,00	21,02	18,19	26,61	1,76
3390	33,00	0,00	20,44	19,96	26,61	0,00
4000	33,00	0,00	20,44	19,96	26,61	0,00
Scenario 2 (with energy cane)						
0	31,46	0,00	21,97	15,3	26,61	4,66
101	32,05	15,19	6,19	17,08	26,61	2,88
198	32,28	21,16	0,00	17,77	26,61	2,18
258	20,76	32,68	0,00	18,99	26,61	0,97
946	20,65	32,79	0,00	19,32	26,61	0,64
1899	20,44	33,00	0,00	19,96	26,61	0,00
2000	20,44	33,00	0,00	19,96	26,61	0,00
3000	20,44	33,00	0,00	19,96	26,61	0,00

[a]MP: Marginal poor soil. [b] FC: Flat land clay soil. [c] FS: Flat land sandy soil. [d] Mac: Macadamia

Table 4-5 results show changes in production decisions by growers at different bagasse price levels. In the optimal solution, Macadamia is selected over timber production due to larger profits realised in macadamia production in clay soils for both scenarios. As the price of bagasse increases for S1 and S2, a point is reached when all land under Macadamia is given up to cane production. This point occurs at R3 390/ton for S1 and R1 899/ton for S2. Considering the decline in area under cane recorded over the years, attaching a value to bagasse can give incentive to cane growers to expand land under cane. This would solve some social and economic problems that the country has been facing due to reduced production of sugarcane. The same analysis was done for the Mid-Illovo and Richmond regions. The results are presented in Appendix I. Although varietal selection is slightly different to that of the Eston Central region, the major similarity is that a point is reached when Macadamia production ceases and all land is cultivated under cane.

4.2.2 Changes in revenue and bagasse quantities

For the sugarcane grower, as the price of bagasse increases under both scenarios, the revenue realised increases (Table 4-6). This is because more tons of fibre are sold with each price increase, leading to more income generation. At this point, it was assumed that the income from sugar and molasses remained constant (although other scenarios are possible and are further investigated in the next sections).

Table 4-6 Percentage change in bagasse quantity produced and revenue with each change in bagasse price.

Bagasse price per ton (Rands)	Cumulative percentage increase in fibre quantity produced	Marginal percentage change in revenue for growers
Scenario 1: Without energy cane (S1)		
0	0,00	0,00
1218	2,84	55,01
3390	4,56	72,79
4000	4,56	11,98
Scenario 2: With energy cane (S2)		
0	0,00	0,00
101	28,38	5,12
198	39,52	5,89
258	60,40	3,78
946	60,90	47,93
1899	61,88	45,02
2000	61,88	3,31
3000	61,88	30,06

Results in Table 4-6 demonstrate an increase in fibre production of under 5% for a scenario without energy cane (S1) and about 62% for a scenario with energy cane (S2). The greatest revenue changes of over 45% are at a price between R946 and R1 899 for S2 and lie between R1 218 and R3 390 for S1. This confirms results that have already been indicated that increased bagasse production is realised at lower prices for a scenario with energy cane. The same analysis was done for the other regions (Mid-Illovo and Richmond). The results obtained are presented in Appendix J. Although bagasse production and revenue changes occur at different prices for the regions, the common result is that, a scenario with energy cane motivates growers to produce energy cane. This results in increased fibre supply at low bagasse prices.

4.3 Sensitivity analysis of the complete partial equilibrium model (sector model)

The analysis in this section fulfils the last objective of the study highlighted in Chapter 1, Section 1.3. The objective is to perform sensitivity analysis on the sector model for a range of cane payment system scenarios, including scenarios in which all biorefinery products are included in the division of proceeds as well as identify the implications of the different scenarios on the division of proceeds. The model was optimised to maximise gross earnings for the purposes of dividing proceeds between Eston growers and millers.

In the literature review, Section 2.3.1, the type of cane payment system in South Africa is described in detail. Total proceeds from sugar and molasses (domestic and export sales) are pooled together and divided between growers and millers at a fixed ratio of 64.3127% and 35.6873% respectively. This is after the deduction of operational and administration costs. The growers share is distributed by the millers via a Relative Recoverable Value (RRV) payment system which rewards growers for the sugar and molasses recovered from their cane at a Recoverable Value tonnage.

A sensitivity analysis on the sector model is carried out for different bagasse prices. This allows for an investigation on the impact of bagasse price changes on mill level and sugarcane biorefinery investment decisions.

4.3.1 Different bagasse prices and their impact on biorefinery investment decisions

The sensitivity analysis began at a bagasse price of zero, which was then increased using the results from Section 4.2.1 for Eston Central as a guiding standard. In the scenario with energy cane, a bagasse price of R258/ton was noted as the point beyond which any further increase did not result in a significant change in fibre quantities supplied to the mill. The bagasse prices where significant changes in fibre supply were observed at R782/ton and R296/ton for Mid-Illovo and Richmond respectively (see Appendix J). An average of R445/ton (including R258/ton for Eston Central) was set as the maximum reasonable price of bagasse in analysing changes in decisions at mill level. Results in Table 4-7 below depict the changes that were identified at mill level as bagasse prices increased. The first analysis was at the calculated equilibrium prices for selected biorefinery products (see Tables 3-25 to 3-28).

Table 4-7 Bagasse price changes and corresponding mill decision changes at calculated equilibrium prices

Bagasse price	**0**	**100**	**140**	**258**	**445**
Total Conventional Cane (CC) harvested *	1 822 178	1 753 628	1 729 330	1 647 269	1 602 424
Total Energy Cane (EC) harvested *	0	374 575	422 731	702 278	782 278
Sucrose tons from CC*	277 398	255 660	252 408	232 912	227 674
Sucrose tons from EC*	0	29 966	33 819	56 182	62 582
Bagasse from CC*	640 150	589 984	582 479	537 489	525 403
Bagasse from EC*	0	194 779	219 820	365 184	406 784
Molasses from CC	85 353	78 664	77 664	71 665	70 054
Molasses from EC*	0	1 498	1 691	2 809	3129
Bagasse to boiler A*	284 256	284 256	none	none	none
Boiler A choice (less efficient)	✓	✓	-	-	-
Bagasse to boiler B*	none	none	300 000	300 000	300 000
Boiler B choice (more efficient)	-	-	✓	✓	✓
Excess bagasse	355 894	500 506	502 300	602 673	632 187
Electricity sold (MWh/year)	8 935	119	23 590	24 714	23 590
Sugar produced*	194 179	199 938	200 358	202 366	203 180
Sugar sold locally*	194 179	199 938	200 358	202 366	203 180
Sugar exported*	0	0	0	0	0
Ethanol produced	0	0	0	0	0
Methanol produced	0	0	0	0	0
Lysine produced	0	0	0	0	0

*All quantities are in tons

According to the data presented in Table 4-7, as the bagasse price increases, changes at the farms are mostly noted in the quantity of Energy Cane (EC) produced. Similar to the results in Section 4.2, more energy cane is produced suggesting that there are changes in variety selection at farm-level as more land is placed under EC. There are no biorefinery investments undertaken by the mill at equilibrium prices for the selected biorefinery products except bagasse electricity sales which increases when a more efficient boiler is used. At a price of R140/ton for bagasse, there is a switch to the use of a more efficient boiler resulting in additional electricity generation.

The quantity of bagasse, molasses and sucrose produced from conventional cane also declines as more energy cane is produced. However, because the type of energy cane used in this study yields some sucrose and molasses, due to its very high cane yields, the sucrose losses are countered by the increase in sucrose production derived from a rise in energy cane production. Therefore, with increased bagasse prices, the quantity of sugar produced also increases. The optimal solution indicates that all the sugar produced is sold on the local market. In reality however, some sugar is exported and this result confirms that it is more profitable to sell sugar locally compared to exporting it. Despite the availability of excess bagasse, the reason why it is not used for methanol production which uses bagasse as a feedstock is that the current methanol prices are not feasible for methanol production to be adopted by the mill. In the next section, adjustments were made on the prices for each of the biorefinery products in order to investigate at which market price biorefinery production begins for the different biorefinery products.

4.3.2 Impact of different biorefinery product market prices on the miller and grower

At calculated equilibrium market prices highlighted in Section 3.5.2 there in no motivation for the miller to undertake any biorefinery production. This is because these prices do not result in an increase in revenue that offsets the associated high fixed and variable costs incurred in biorefinery production.

Market prices for each of the biorefinery products had to be inflated for biorefinery production to begin. When the price of methanol is raised from R6 300 to R12 000/ton the mill produces 18 000 tons of methanol. Beyond this price, any further adjustments to the price led to no changes in the quantity of methanol produced. Altering the methanol price does not influence any production decisions at farm-level.

Forty-five thousand tons of ethanol are produced at a price of R20 000/ton. Increasing the price of lysine to R40 000/ton results in lysine production of 65 000 tons, the maximum capacity the mill can produce. This diversion of sucrose to ethanol or lysine production results in less sugar production. Table 4-8 below shows the reduction in sugar production at the prices where production begins for each biorefinery product. The analysis was done while adjusting the market price for one biorefinery product at a time and keeping prices for the other products constant.

Table 4-8 Quantities of biorefinery products, cane harvested and sugar produced at optimum prices and zero bagasse price

Biorefinery product **Prices** **Quantities (tons)**	All biorefinery products at equilibrium prices	Ethanol at R20 000	Lysine at R40 000	Methanol at R12 000
Total sugar produced	194 179	142 005	73 168	194 179
Total Conventional Cane harvested	1 822 178	1 822 178	1 822 178	1 822 178
Total Energy Cane harvested	0	0	0	0
Quantity of biorefinery product produced	0	45 000	65 000	18 000

Lysine production is selected over ethanol production when the model is optimised at the prices which allow for production of all biorefinery products. Table 4-9 below illustrates the changes in sugar, methanol, ethanol and lysine quantities when all products are included at their optimum prices with two scenarios when lysine is set at R30 000/ton and R40 000/ton.

Table 4-9 Quantities of biorefinery products at optimum prices with lysine at R40 000/ton and R30 000/ton

Bagasse price	**0**	**100**	**140**	**258**	**445**
Scenario 1 All biorefinery products set at optimum prices with lysine at R40 000/ton					
Sugar	73 168	78 927	79 348	81 355	82 169
Ethanol	0	0	0	0	0
Methanol	18 000	18 000	18 000	18 000	18 000
Lysine	65 000	65 000	65 000	65 000	65 000
Scenario 2 All biorefinery products set at optimum prices with lysine at R30 000/ton					
Sugar	150 000	150 000	150 000	150 192	151 006
Ethanol	38 104	43 071	43 434	45 000	45 000
Methanol	22 499	22 499	22 499	22 499	18 000
Lysine	0	0	0		0

Results in Table 4-9 confirm that market prices have a great influence on mill investment decisions. Adjusting the lysine price from R40 000/ton to R30 000/ton leads to a switch from lysine production to ethanol production. The two products compete for the same raw material and as such model optimisation results in a choice of product that is profitable relative to investment costs. Methanol production on the other hand remains unaffected showing constant production levels as it uses bagasse as a raw material. It can be concluded that mill biorefinery investments depend on market prices as well as the type of feedstock.

An assessment of changes in total proceeds with and without biorefinery products was carried out. The results are presented in the next section.

4.3.3 Implications of a sugarcane biorefinery on the total proceeds

As explained earlier, all proceeds from the sale of sugar and molasses in South Africa are shared between growers and millers at a fixed ratio of 64,3127% and 35,6873% respectively. Different scenarios for total proceeds are presented in Figure 13.

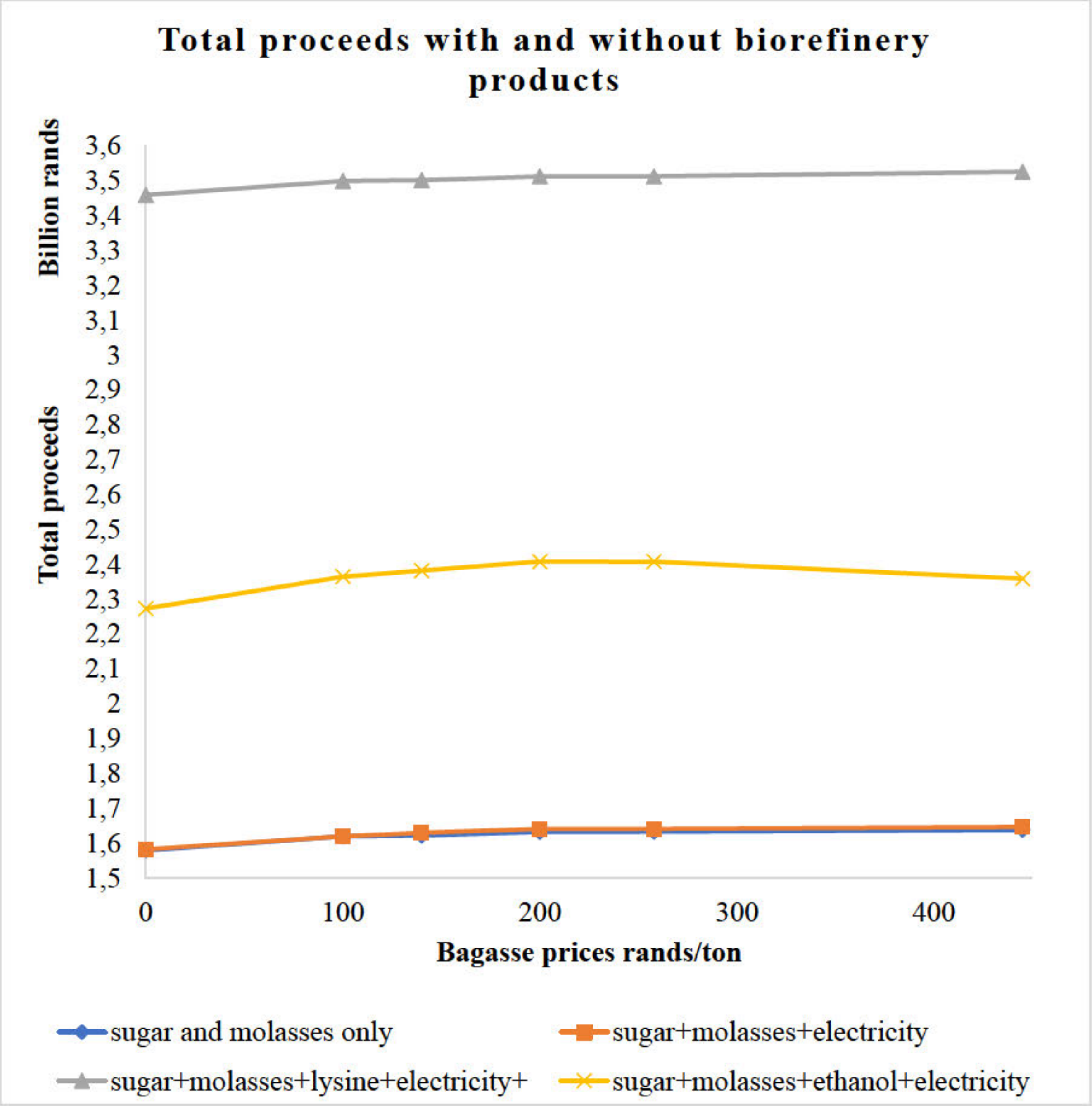

Figure 13 A graphical presentation of changes in total proceeds at varying bagasse prices with and without biorefinery products

The graphs in Figure 13 show that the wider the biorefinery product portfolio, the greater the proceeds. The greatest revenue is realised in a scenario that includes lysine, electricity, sugar and molasses. The sugar produced in all scenarios is all sold locally and the prices for the biorefinery products have been set at very high levels. In reality however, some sugar is exported and the biorefinery product market prices are not that high. This suggests that if biorefinery investments are to be undertaken there will be need under the current status quo, for some sort of protection in the form of subsidies to be offered by the government otherwise it is not feasible to produce any of the biorefinery products used in this study. Dividing these proceeds or sharing the revenue will entirely depend on the regulation and policies set up by relevant stakeholders. As indicated in the literature review (Section 2.3.2) the type of revenue sharing agreement, the products included in revenue sharing can differ. The literature did show that biorefinery products included in the division of proceeds are successfully produced in those countries e.g. electricity generation in Mauritius, bio-ethanol in Brazil and Colombia.

4.4.4 Implications of bagasse prices on cane prices

Using the formula outlined in Section 3.29, cane prices were calculated and measured against the cane price for the 2020/21 season which was R613. The price of bagasse was set at R445/ton as identified in Section 4.2. The direct relationship between fibre and bagasse quantities as highlighted in Section 3.4.1 implies that the price of one ton of fibre is double the price of a ton of wet bagasse (50% moisture content). In this instance, at a price R445 per ton of bagasse, the price for a ton of fibre is R890. Table 4-10 presents the components included in calculating cane prices for conventional and energy cane as well as the final cane prices with inclusion of fibre.

Table 4-10 An outline of the average content levels, prices and cane prices of conventional cane and energy cane

Cane Variety	**Fibre %**	**Sucrose %**	**Molasses %**
Conventional Cane	15	12	4
Energy cane	26	8	0,4
Prices for each component			
	Fibre	**Sucrose**	**Molasses**
Prices (Rand/ton)	890	5 000,39	958,29
Final cane prices			
Cane variety	**Price Rand/ton**	**Percentage increase relative to the current cane price of R613**	
Conventional Cane	772	26	
Energy cane	635	4	

The results show an increase in the cane price for both conventional and energy cane when the price of fibre is set at R890. A percentage increase of 26% is noted for the conventional cane price compared to a 4% increase for energy cane when fibre is included. This is attributed to very low levels of molasses produced per ton of energy cane crushed. This result does confirm that introducing a fibre price can increase the overall profitability of sugarcane growing as illustrated by higher cane prices. It is important to note that this is an average fibre price with average fibre and sucrose content levels. These components differ with each cultivar and therefore cane prices will differ by cultivar.

4.4.5 Is a sugarcane biorefinery economically viable?

In light of the Biofuels feedstock protocol stating that the sugarcane equivalent of additional sugar could be diverted to production of biofuels, there is a lot to consider in using this sucrose for biofuel production. Viability of a sugarcane biorefinery is dependent on a number of factors that include feedstock supply and the right biorefinery product market prices which make biorefinery production feasible. Farmers will not produce large quantities of biomass unless they can envisage the profitability from their supply of feedstock, and biorefinery investors will not make huge investments unless they are assured of long-term consistent feedstock supplies that are reasonably priced. Therefore, it is important to address the issues that will ensure increased feedstock supply. The results have demonstrated that introducing a high fibre variety (energy cane) and including a price for bagasse in cane payment are two factors that can increase feedstock supply.

The sugarcane-based value-chain diversification strategy indicated by the Sugarcane Value Chain Master Plan to 2030 may prove difficult to achieve under current biorefinery product pricing conditions. In this study, for the products considered, it is clear that diversification is possible only when market prices are much higher than the prevailing prices. In a scenario where biorefinery products share the same raw material, market prices and investment costs are a major determinant in the selection of which products could be produced. In the case of lysine and ethanol which both use sucrose as a raw material, there was never a point when both products were produced at the same time, lysine was selected over ethanol when the price of lysine was much higher than the price of ethanol and vice versa. Cogeneration of electricity for sale to the national grid seems to be the likely viable option as it does not involve huge investment costs and also makes use of bagasse which has currently no other use in the mill except burning it for fuel.

Biorefinery product decision making should be milling area and region specific with consideration of the distance of the sugarcane farms to the mill, soil properties and climatic conditions in the area. It is not a one size fits all as shown by the differing farm decisions in each region for the Eston milling area. If high fibre (EC) cane is profitably grown in the Eston milling area, a fibre-based biorefinery product makes potentially more sense there, while if sugarcane (high sugar contents) is better grown in Mpumalanga, then a biorefinery product from sugar would be better suited for them. This would be important in terms of diversifying the sector, and not have different mills/companies enter into artificial competition.

Can energy cane be a solution to some challenges the industry is facing?

Growing cane specifically for fibre or with higher fibre content may be a route worth pursuing for SA's sugar industry. In an era where sugarcane with high fibre is now recognised as a good biorefinery crop, on-going research in countries such as Mauritius and U.S.A. are mapping the future for tomorrow's sugarcane industries. Apart from various value added products that can be potentially produced from fibre in energy cane, there are a number of benefits realised from growing energy cane compared to conventional cane. The plants demand less water hence would better cope with drought conditions. Additionally, they are more resistant to pests and diseases resulting in low use of pesticides, herbicides and fertiliser. This results in low input costs thus benefitting the smallholder grower whose production levels have declined over the years due to lack of access to finance. In addition, considering the droughts that this country has been facing, reduced local sugar demand due to the implementation of the Health Promotion Levy, and rising input costs, energy cane could possibly help alleviate these problems.

In 2015/16, the Umzimkulu mill was closed due to poor cane supply as a result of drought and this had a negative effect on the industry, the local community and the country as a whole. Once energy cane is adopted, a potential scenario can include harvesting cane only during off season for fibre, or both fibre and sugar. Another scenario could involve parallel processing of both energy cane and conventional cane for both sugar and fibre. Consequently, if some of the sugarcane was produced entirely for its fibre content, then the harvest timelines determined by sucrose accumulation would no longer hold. In both instances, it becomes possible for mills to operate throughout the year with continuous cane supply. This, however, is subject to mill maintenance requirements, considering that in SA mills generally carry out major maintenance work in the off-crop. A study by Kim and Day (2011) showed that energy cane production had the potential to increase feedstock supply and increase ethanol production.

Dextran issues have also been a cause for concern in SA mills. Dextran is due to microbial activity emanating mostly from cane deterioration, which results in reduced quality and quantity of sugar produced, principally leading to revenue loss. Once the focus shifts from sugar production only to other or additional products from fibre in energy cane, dextran problems may end. Sucrose content is lower in energy cane and to maximise fibre at harvest, the cane can be green cane harvested. This would reduce dextran formation as a result of burning cane before harvest and bring relief to the industry.

Expansion of the product portfolio to include biorefinery products from fibre would require an incentive to be in place to protect those local markets that the products made from fibre are aimed for, from international price dumps. More research would need to be done regarding this type of cane to determine the suitability to SA climatic conditions as well as to identify and calculate costs linked to any agronomic and management issues that could arise from growing energy cane. Moreover, cane crushing costs incurred by the miller to crush high fibre cane in existing mills would need to be quantified in order to certify the profitability of producing energy cane.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Purpose of the study and conclusions

The sugar industry has seen a decline in the area under cane over the years due to the declining profitability of the industry. In Eston, reduced production and area under cane has been mainly noted for the small scale sugarcane grower due to high input costs and lack of access to finance amongst other reasons. The gross sugar production in South Africa (SA) tends to exceed the quantity demanded locally. Surplus sugar is sold in the global market at very low prices that are typically below the cost of sugar production in SA. The South African Sugarcane Value Chain Master Plan to 2030 signed in 2020 has a special focus on feasible and attractive sugarcane-based biorefinery products opportunities locally and internationally. A sugarcane biorefinery requires a reliable feedstock and farmers will not produce large quantities of biomass unless they can envisage the profitability from their supply of feedstock. Biorefinery investors will not make huge investments unless they are assured of long term consistent feedstock supplies that are reasonably priced. The study uses a partial equilibrium model to investigate the implications of establishing a sugarcane biorefinery on both farm and mill level decisions.

Three mathematical linear programming representative models of a ‘typical’ sugarcane farm for the Eston Cane Supply area were constructed with the inclusion of a high fibre variety of cane, energy cane. These were combined with a biorefinery appended to the mill representative model for a generic South African sugar mill whose demand for molasses, sucrose and bagasse was derived from the domestic and export market demands for methanol, ethanol, lysine and co-generation of electricity. Model optimisation showed that feedstock supplies can be increased much quicker by placing a value on bagasse as well as incorporating a high fibre variety (energy cane). As the bagasse price is altered, changes at farm-level include an increase in the area under cane as well as production of high fibre varieties. At mill level, a shift in the use of a more efficient boiler is noted at a bagasse price of R140 resulting in increased electricity production. Although sugar production is reduced when ethanol or lysine production is undertaken, the high market prices at which the biorefinery products sell keep the revenue high. The viability of the sugarcane biorefinery will depend on biorefinery product market prices, a reliable feedstock supply as well as high capacities of production for each of the products. A large capacity will result in the miller benefiting from economies of size.

While introducing energy cane and placing value on bagasse helps increase feedstock supply, a new cane payment system needs to drive the correct incentives as well as reward efficiencies and investments in the production processes of additional biorefinery products.

5.2 Recommendations

This section presents recommendations for the sugar industry that could aid in driving the product diversification strategy supported by the South African Sugarcane Value Chain Master Plan to 2030.

5.2.1 Modifying cane payment

Depending on the biorefinery product choices, the cane payment system should incentivise growers to increase production of the required feedstock. Modifying the current cane payment system to include a price for fibre is a welcome development that could be a game changer in the SA sugar industry. Bagasse can also be used to generate other co-products such as specialty sugars, compounds from lignin (bioactives, hydrocarbons, paints and resins), organic acids, fermentation products and energy products such as hydrogen, biodiesel and methane. Users of sugarcane fibre may be willing to pay higher prices for it to incentivise an increase in supply of the fibre. Interestingly, in Australia, it has been estimated that the cost of bagasse could increase from $80 to $1 000/ton (approx. R11 000/t) due to the potential value addition from co-products from the bagasse component lignin (unpublished data [3]).

The results showed that placing a value on fibre increases cane production and results in changes in grower production decisions. This has implications for the pricing of cane and the final division of proceeds from sugarcane production, milling and bio-refinery operations. Brazil’s payment system is a quality-based system incorporating the quality of cane and prices of sugar, hydrous ethanol and anhydrous ethanol. This coupled with over 40 years of extensive government policy initiatives has made Brazil very successful in bio-ethanol production.

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[3] Campbell, G (2017). Daily Mercury [Internet] https://www.dailymercury.com.au/news/1000-a-ton-for-bagasse/3214261/ [Accessed 19 February 2019]

5.2.2 Division of proceeds

The literature review demonstrated various options for dividing proceeds carried out by countries that obtain revenue not only from sugar and molasses sales. Sales from ethanol and bagasse electricity are some of the additional revenue sources for countries like Brazil and Mauritius. In Mauritius growers also obtain a percentage of revenue from any bagasse use other than powering the sugar factory. Brazil ethanol sales are shared at 61.2% to growers. The South African sugar industry should adopt a similar approach for any other biorefinery product sales in addition to sugar and molasses.

5.2.3 Government support and regulatory policies

Strong governmental support and regulatory policies in Brazil and Colombia have made the countries top world sugar and ethanol producers. Government, among other things; provides financial and tax incentives, mandates minimum blending of ethanol into gasoline, the Brazilian government has banned the private purchase of diesel-powered vehicles since the 1970s and encourages manufacturing of flex-fuel vehicles. While South Africa is making progress in establishing policies that support biofuel production, implementation of these policies will ensure viability of sugarcane biorefineries in the country by providing a ready market for biorefinery products. There will also be a need to protect the biorefinery industries since the current market prices for the products are too low to incentivise biorefinery production.

5.2.4 Growing the local sugar market

Continued effort through campaigns should be made to secure a larger local sugar market share as it is more profitable to sell sugar locally and it increases the revenue to the industry.

5.2.5 Economies of size and biorefinery product selection

It will be important to consider expanding the maximum production capacity for the biorefinery products. This ensures that the biorefinery investors benefit from economies of size giving a cost advantage due to reduced per unit fixed and variable costs of production. This would call for a reliable feedstock supply and operational efficiency to ensure operation at maximum capacity at all times.

Apart from biorefinery products such as ethanol that could spark universal interest amongst milling companies, selection of biorefinery products will depend on the product portfolio a company already has. Milling companies would need to weigh the cost of producing products that are different to what they already produce in comparison to expanding what already exists. This means for a food industry supplier, making alternative sweeteners, emulsifiers and flavorants may be the best way forward as they can use existing customer relations for sales. If the milling company has a biorefinery producing furfural, as an example, and the market outlook for furfural is good, it is much easier for them to rather build another furfural plant.

5.2.6 Introducing energy cane

While energy cane management and establishment costs are yet to be established, it is possible that the benefits realised from this cultivar may outweigh the costs. Where bagasse is a feedstock for selected biorefinery products, introducing a high fibre variety will increase the quantity of fibre supplied by the growers. It has an added advantage of possible harvesting at any time of the year making it possible for mills to operate throughout the year. There will be a need to invest in more efficient steam boilers that would allow for surplus electricity to be produced in the event that bagasse electricity becomes an option. Costs incurred in buying coal for fuel in instances of bagasse unavailability can be cut with the use of more efficient steam boilers.

5.3 Limitations of the study

The limitations of the study and opportunities for further research are presented in this section:

- This study is a proof of concept that only represents one cane supply area and is thus not representative of the whole SA sugar industry. Future research could expand the partial equilibrium model to include the other cane supply areas in the industry. In doing so, the relatively high cost of transporting cane, which limits the viable cane supply area for a biorefinery would need to be considered.

- It was difficult to secure cost data for the biorefinery production processes that use bagasse as a feedstock considering that research is still on-going on the techno-economics of other biorefinery products.
- The study includes a hypothetical cultivar of cane, energy cane. There is need therefore to further investigate the suitability of this type of cane to SA climatic conditions as well as to identify and calculate costs linked to any agronomic and management issues that could arise from growing energy cane. Moreover, cane crushing costs incurred by the miller to crush high fibre cane in existing mills would need to be quantified in order to certify the profitability of producing energy cane.
- Focus was on large scale commercial growers only, future studies could also incorporate the small scale growers in order to establish their responses to a modified cane payment
- The biorefinery appended to the mill model is built on a set of assumptions that are dependent on policies that still need to be effected to make these assumptions a reality.

5.3.1 Potential areas for further study

Other opportunities for research arising from this study include:

- The implications on potential investment decisions by the grower or third-party investors may need to be considered in more detail, especially if cane payment restricted the likelihood of future industry investments in capital.
- The impact of varying the bagasse price on the miller revenue particularly the impact of paying growers a share of the bagasse revenue can be investigated. What is the impact of this share to the grower on the economic viability of an investment in cogeneration or biorefinery assets- not just the gross earnings but the feasibility of an economic return on the capital invested?
- Further sensitivity analysis around key assumptions made in constructing the mill model could aid in validating some of the output on the optimal biorefinery product choices.

This study has demonstrated and confirmed that biorefinery production is dependent on the product market prices, capacity of production as well as feedstock supply. Pricing bagasse has implications on the cane price which in turn affects farm production decisions. While it is possible to resuscitate the industry, establishing biorefineries requires systems thinking that calls for stakeholders to look at the whole supply chain in totality as the decisions of one affect the other.

Biorefinery product decision making should be milling area and region specific with consideration of the distance of the sugarcane farms to the mill, soil properties and climatic conditions in the area. It is not a one size fits all as shown by the differing farm decisions in each region for the Eston milling area. If high fibre (EC) cane is profitably grown in the Eston milling area, a fibre-based biorefinery product makes potentially more sense there, while if sugarcane (high sugar contents) is better grown in Mpumalanga, then a biorefinery product from sugar would be better suited for them. This would be important in terms of diversifying the sector, both in terms of crops and product portfolio. A prerequisite would be the introduction of a milling area-specific cane payment, dependent on the product portfolio. This approach would allow companies to make biorefinery product choices based on the productive strengths of the respective farming area, and avoid artificial competition between different mills/companies.

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APPENDIX A. Enterprise budget in a typical year per hectare for popular varieties in Eston Central

MP N12

	2017/18	**2016/17**	**2015/16**	**2014/15**	**2013/14**	**2012/13**	**2011/12**
RV price per ton[a]	3817,90	4187,11	5053,05	3460,60	3095,81	3035,97	3278,31
Average yield RV (Tons per hectare)[b]	0,12	0,13	0,11	0,11	0,13	0,13	0,13
Average expected tons/ha[c]	100,00	77,13	85,30	61,40	91,64	104,45	99,13
Income ($^{[a*b*c]}$*51.25%) * **	22851,99	21414,91	23739,54	12454,13	18867,26	20945,94	21485,42

Allocated Costs							
Cane planting costs-Mechanical land preparation							
Land preparation	3253,00	2824,00	2630,00	2840,00	2583,00	2379,00	2028,00
Hand planting	2770,00	2565,00	2406,00	2793,00	2625,00	2102,00	1880,00
Seedcane	8699,00	6866,00	6158,00	5540,00	5018,00	5139,00	4496,00
Fertiliser and lime	7525,00	7705,00	6884,00	4153,00	4379,00	3576,00	3352,00
Weed control	2677,00	2498,00	2272,00	2522,00	1878,00	1670,00	1425,00
Sundries and contingencies	2493,00	2246,00	2035,00	2677,00	1648,00	1486,00	1318,00
Total cane planting costs[d]	27417,00	24704,00	22385,00	20525,00	18131,00	16352,00	14499,00
Adjusted planting cost (PC) ([d]*11.25%) ***	3084,41	2779,20	2518,31	2309,06	2039,74	1839,60	1631,14
Harvesting costs							
Cutting of burnt cane	5877,00	4213,46	4370,75	2920,92	4098,17	3672,44	2968,85
Infield-cane haulage	2528,00	1713,77	1666,75	1319,88	1723,76	1787,13	1621,72
Loading &transhipment of burnt cane	1402,00	1093,66	988,62	798,07	1108,85	1082,10	971,44
Total harvesting costs[e]	9807,00	7026,13	5038,86	6930,78	6541,67	5562,01	5562,01
Adjusted harvesting cost (HC) ([e]*52%) ***	5026,09	3600,89	2582,42	3552,02	3352,60	2850,53	2850,53
Ratoon management costs							
Field management	528,28	524,37	469,87	433,18	403,69	327,20	307,11
Fertilizer	3233,00	3232,97	3125,82	3042,17	2957,79	2739,20	2586,62
Weed control	2463,00	2486,68	2331,64	2167,17	2009,21	1604,55	1493,59
Sundries and contingencies	622,46	622,46	585,25	565,87	532,93	497,66	434,87
Total ratoon costs[f]	6847,03	6711,45	6348,11	6050,44	5498,96	5057,65	3328,60
Adjusted ratoon cost (RC) ([f]*40%) ***	2738,81	2684,58	2539,25	2420,17	2199,58	2023,06	1331,44
Green manuring[g]	3440,24	3543,83	3910,82	4020,91	3749,03	3248,71	3018,27
Adjusted green manuring (GM) [g]*11.25%) ***	387,03	398,68	439,97	452,35	421,77	365,48	339,56
Eldana control (**E**)	2028,75	2028,75	2028,75	2028,75	2028,75	2028,75	2028,75
Total variable costs (TVC) (PC+HC+RC+GM+E)	13265,09	11492,10	10108,69	10762,36	10042,44	9107,42	8181,41
Gross margin (Income-TVC)	9586,90	9922,81	13630,85	1691,76	8824,82	11838,52	13304,00

The budgets following only fully capture details in the differences in yield and summarises other costs.

MPN31

	2017/18	**2016/17**	**2015/16**	**2014/15**	**2013/14**	**2012/13**	**2011/12**
RV price per ton[a]	3817,90	4187,11	5053,05	3460,59	3095,81	3035,97	3278,31
Average yield RV (Tons per hectare)[b]	0,12	0,12	0,10	0,11	0,13	0,14	0,13
Average expected tons/ha[c]	95,00	85,00	65,00	51,00	86,00	90,00	82,00
Income ([a*b*c]*51.25%) ***	22063,94	21967,32	16629,55	10268,71	17425,29	18954,96	17925,15

Total variable costs (TVC)	12880,07	10491,96	9608,26	10496,12	9638,77	8587,84	8225,41
Gross margin (Income-TVC)	9183,87	11475,36	7021,30	-227,41	7786,52	10367,12	9699,74

FC N48

	2017/18	**2016/17**	**2015/16**	**2014/15**	**2013/14**	**2012/13**	**2011/12**
RV price per ton[a]	3817,90	4187,11	5053,05	3460,59	3095,81	3035,97	3278,31
Average yield RV (Tons per hectare)[b]	0,12	0,13	0,11	0,12	0,13	0,11	0,13
Average expected tons/ha[c]	110,00	85,06	86,10	84,77	94,52	105,70	100,00
Income ($^{[a*b*c]}$*51.25%) ***	25970,89	23927,54	24721,31	18680,71	18979,70	18509,31	22541,64
Allocated Costs							
Total variable costs (TVC)	15623,06	13643,05	12930,19	11430,76	11434,86	10463,35	9402,37
Gross margin (Income-TVC)	10347,83	10284,49	11791,13	7249,95	7544,84	8045,96	13139,28

FS N54

	2017/18	**2016/17**	**2015/16**	**2014/15**	**2013/14**	**2012/13**	**2011/12**
RV price per ton[a]	3817,90	4187,11	5053,05	3460,59	3095,81	3035,97	3278,31
Average yield RV (Tons per hectare)[b]	0,10	0,12	0,10	0,12	0,13	0,14	0,13
Average expected tons/ha[c]	168,00	153,33	118,67	120,00	160,00	157,33	152,00
Income ($^{[a*b*c]}$*51.25%) ***	43816,80	49539,00	40962,77	32060,01	43016,82	43968,13	44088,90
Allocated Costs							
Total variable costs (TVC) (PC+HC+RC+GM+E)	20397,80	15536,04	15172,09	16311,97	14347,16	12799,84	12373,78
Gross margin (Income-TVC)	23419,00	34002,95	25790,68	15748,04	28669,66	31168,29	31715,12

MP Energy Cane

	2017/18	**2016/17**	**2015/16**	**2014/15**	**2013/14**	**2012/13**	**2011/12**
RV price per ton[a]	3817,90	4187,11	5053,05	3460,59	3095,81	3035,97	3278,31
Average yield RV (Tons per hectare)[b]	0,08	0,07	0,06	0,07	0,09	0,07	0,08
Average expected tons/ha[c]	170,00	140,00	130,00	180,00	190,00	160,00	120,00
Income ($^{[a*b*c]}$*51.25%) ***	34617,36	28138,79	27591,04	30108,68	33333,20	23641,28	21244,52
Allocated Costs							

Total variable costs (TVC)	20451,94	17483,62	15775,72	18128,02	17390,64	13825,74	11206,03
Gross margin (Income-TVC)	14165,42	10655,17	11815,32	11980,66	15942,56	9815,54	10038,49

FC N50

	2017/18	**2016/17**	**2015/16**	**2014/15**	**2013/14**	**2012/13**	**2011/12**
RV price per ton[a]	3817,90	4187,11	5053,05	3460,59	3095,81	3035,97	3278,31
Average yield RV (Tons per hectare)[b]	0,12	0,13	0,10	0,12	0,12	0,12	0,12
Average expected tons/ha[c]	101,00	89,36	92,30	77,90	114,32	112,94	105,00
Income ([a*b*c]*51.25%) ***	23154,55	23989,95	25086,65	15955,83	22595,86	21741,76	21848,06
Allocated Costs							
Total variable costs (TVC)	13463,19	11882,51	10900,63	11738,74	10509,82	9352,21	8977,43
Gross margin (Income-TVC)	9691,36	12107,44	14186,02	4217,09	12086,05	12389,55	12870,62

APPENDIX B. Enterprise budget in a typical year per hectare for popular varieties in Mid-Illovo

MPN12

	2017/18	2016/17	2015/16	2014/15	2013/14	2012/13	2011/12
RV price per ton[a]	4502,98	4187,11	5009,92	4738,99	4516,24	4493,04	4555,59
Average yield RV (Tons per hectare)[b]	0,13	0,13	0,12	0,13	0,14	0,13	0,14
Average expected tons/ha[c]	109,40	102,42	100,22	86,40	95,04	90,72	96,77

Income ([a*b*c]*51.25%) * **	32631,97	28893,60	30493,44	27517,37	31017,69	27514,81	31292,30
Allocated Costs							
Cane planting costs-Mechanical land preparation							
Land preparation	3253,00	2824,00	2630,00	2840,00	2583,00	2379,00	2028,00
Hand planting	2770,00	2565,00	2406,00	2793,00	2625,00	2102,00	1880,00
Seedcane	8699,00	6866,00	6158,00	5540,00	5018,00	5139,00	4496,00
Fertiliser and lime	7525,00	7705,00	6884,00	4153,00	4379,00	3576,00	3352,00
Weed control	2677,00	2498,00	2272,00	2522,00	1878,00	1670,00	1425,00
Sundries and contingencies	2493,00	2246,00	2035,00	2677,00	1648,00	1486,00	1318,00
Total cane planting costs[d]	27417,00	24704,00	22385,00	20525,00	18131,00	16352,00	14499,00
Adjusted planting cost (PC) ([d]*11.25%) * **	3084,41	2779,20	2518,31	2309,06	2039,74	1839,60	1631,14
Harvesting costs							
Cutting of burnt cane	6429,25	5595,30	5135,48	4110,91	4250,19	3189,72	2898,20
Infield-cane haulage	2765,55	2275,81	1958,38	1857,60	1787,70	1552,22	1583,12
Loading and transhipment of burnt cane	1533,74	1435,95	1421,18	1001,38	1235,52	1097,71	1002,52
Total harvesting costs[e]	10728,54	9307,07	8515,03	6969,89	7273,41	5839,65	5483,84
Adjusted harvesting cost (HC) ([e]*52%) * **	5498,38	4769,87	4363,95	3572,07	3727,62	2992,82	2810,47
Ratoon management costs							
Field management	528,28	524,37	469,87	433,18	403,69	327,20	307,11
Fertilizer	3233,00	3232,97	3125,82	3042,17	2957,79	2739,20	2586,62
Weed control	2463,00	2486,68	2331,64	2167,17	2009,21	1604,55	1493,59
Sundries and contingencies	622,46	622,46	585,25	565,87	532,93	497,66	434,87
Total ratoon costs[f]	6847,03	6866,48	6512,59	6208,40	5903,62	5168,61	4822,19
Adjusted ratoon cost (RC) ([f]*40%) * **	2738,81	2746,59	2605,03	2483,36	2361,45	2067,44	1928,88
Green manuring[g]	3440,24	3543,83	3910,82	4020,91	3749,03	3248,71	3018,27
Adjusted green manuring (GM) [g]*11.25%) * **	387,03	398,68	439,97	452,35	421,77	365,48	339,56
Eldana control (**E**)	2028,75	2028,75	2028,75	2028,75	2028,75	2028,75	2028,75
Total variable costs (TVC) (PC+HC+RC+GM+E)	13737,38	12723,10	11956,02	10845,59	10579,32	9294,09	8738,79
Gross margin (Income-TVC)	18894,59	16170,50	18537,42	16671,78	20438,37	18220,72	22553,51

FCN12

	2017/18	2016/17	2015/16	2014/15	2013/14	2012/13	2011/12
RV price per ton[a]	4502,98	4187,11	5009,92	4738,99	4516,24	4493,04	4555,59
Average yield RV (Tons per hectare)[b]	0,13	0,13	0,12	0,13	0,14	0,13	0,14
Average expected tons/ha[c]	113,96	106,69	104,40	90,00	99,00	94,50	100,80

Income ([a*b*c]*51.25%) ***	33991,63	30097,50	31764,00	28663,93	32310,10	28661,26	32596,14
Allocated Costs							
Total variable costs (TVC)	13579,45	12930,59	11999,27	11059,46	10688,98	9334,52	8826,96
Gross margin (Income-TVC)	20412,18	17166,91	19764,72	17604,47	21621,12	19326,74	23769,18

FS N12

	2017/18	2016/17	2015/16	2014/15	2013/14	2012/13	2011/12
RV price per ton[a]	4502,98	4187,11	5009,92	4738,99	4516,24	4493,04	4555,59
Average yield RV (Tons per hectare)[b]	0,13	0,13	0,12	0,13	0,14	0,13	0,14
Average expected tons/ha[c]	126,62	118,54	116,00	100,00	110,00	105,00	112,00
Income ([a*b*c]*51.25%) ***	37768,48	33441,67	35293,33	31848,81	35900,11	31845,85	36217,94
Allocated Costs							
Total variable costs (TVC)	14602,87	13483,63	12488,96	11480,12	11115,34	9671,55	9149,03
Gross margin (Income-TVC)	23165,62	19958,04	22804,37	20368,69	24784,77	22174,30	27068,90

MP N31

	2017/18	2016/17	2015/16	2014/15	2013/14	2012/13	2011/12
RV price per ton[a]	4502,98	4187,11	5009,92	4738,99	4516,24	4493,04	4555,59
Average yield RV (Tons per hectare)[b]	0,12	0,12	0,10	0,11	0,13	0,13	0,13
Average expected tons/ha[c]	90,00	125,16	80,00	70,00	95,00	100,00	85,00
Income ([a*b*c]*51.25%) ***	24348,22	31893,29	19771,24	18638,37	28668,89	30909,41	25704,71
Allocated Costs							
Total variable costs (TVC)	12628,76	13652,60	10840,06	10107,35	10432,20	9439,61	8311,68
Gross margin (Income-TVC)	11719,46	18240,69	8931,18	8531,03	18236,69	21469,80	17393,03

FC N48

	2017/18	2016/17	2015/16	2014/15	2013/14	2012/13	2011/12
RV price per ton[a]	4502,98	4187,11	5009,92	4738,99	4516,24	4493,04	4555,59
Average yield RV (Tons per hectare)[b]	0,13	0,13	0,11	0,13	0,13	0,15	0,13
Average expected tons/ha[c]	141,77	115,39	116,00	100,00	110,00	120,00	115,00

Income ($^{[a*b*c]}$*51.25%) ***	42803,72	31520,14	34112,45	30628,04	32928,84	42550,94	35172,86
Allocated Costs							
Total variable costs (TVC)	15623,06	13643,05	12930,19	11430,76	11434,86	10463,35	9402,37
Gross margin (Income-TVC)	27180,66	17877,09	21182,26	19197,28	21493,98	32087,60	25770,49

FC N54

	2017/18	2016/17	2015/16	2014/15	2013/14	2012/13	2011/12
RV price per ton^{a}	4502,98	4187,11	5009,92	4738,99	4516,24	4493,04	4555,59
Average yield RV (Tons per hectare)^{b}	0,13	0,13	0,11	0,13	0,13	0,12	0,12
Average expected tons/ha^{c}	172,86	139,00	138,00	110,00	120,00	140,00	135,00
Income ($^{[a*b*c]}$*51.25%) ***	65997,31	48634,22	49575,94	45330,57	46609,95	50030,96	49612,85
Allocated Costs							
Total variable costs (TVC)	17075,12	14470,65	13449,35	11934,76	11536,08	10826,50	9840,13
Gross margin (Income-TVC)	48922,19	34163,57	36126,59	33395,81	35073,87	39204,46	39772,73

SR N54

	2017/18	2016/17	2015/16	2014/15	2013/14	2012/13	2011/12
RV price per ton^{a}	4502,98	4187,11	5009,92	4738,99	4516,24	4493,04	4555,59
Average yield RV (Tons per hectare)^{b}	0,13	0,13	0,11	0,13	0,13	0,12	0,12
Average expected tons/ha^{c}	150,00	125,00	115,00	110,00	120,00	125,00	125,00
Income $^{([a*b*c]*51.25\%)}$ ***	57268,24	43735,81	41313,28	45330,57	46609,95	44670,50	45937,83
Allocated Costs							
Total variable costs (TVC)	15925,86	13817,51	12478,42	11934,76	11536,08	10345,03	9552,56
Gross margin (Income-TVC)	41342,38	29918,30	28834,87	33395,81	35073,87	34325,47	36385,27

MP Energy cane

	2017/18	2016/17	2015/16	2014/15	2013/14	2012/13	2011/12
RV price per ton^{a}	4502,98	4187,11	5009,92	4738,99	4516,24	4493,04	4555,59
Average yield RV (Tons per hectare)^{b}	0,09	0,07	0,06	0,07	0,08	0,07	0,09
Average expected tons/ha^{c}	200,00	194,00	122,00	105,00	170,00	187,00	173,00

Income ([a*b*c]*51.25%) * **	54038,40	37909,20	24449,63	23222,21	40949,31	39211,19	47289,39
Allocated Costs							
Total variable costs (TVC)	22163,14	21671,42	16550,84	15076,06	18860,08	19309,29	17969,66
Gross margin (Income-TVC)	31875,26	16237,78	7898,79	8146,15	22089,24	19901,90	29319,73

SR N50

	2017/18	2016/17	2015/16	2014/15	2013/14	2012/13	2011/12
RV price per ton[a]	4502,98	4187,11	5009,92	4738,99	4516,24	4493,04	4555,59
Average yield RV (Tons per hectare)[b]	0,12	0,12	0,10	0,13	0,13	0,12	0,12
Average expected tons/ha[c]	135,00	129,00	121,00	100,00	120,00	125,00	130,00
Income ([a*b*c]*51.25%) * **	37859,09	33633,54	31773,97	31239,58	35829,61	34626,56	36846,86
Allocated Costs							
Total variable costs (TVC)	15986,29	14726,31	13344,66	12018,89	12094,23	10826,50	10144,94
Gross margin (Income-TVC)	21872,80	18907,23	18429,31	19220,69	23735,38	23800,07	26701,92

FS N52

	2017/18	2016/17	2015/16	2014/15	2013/14	2012/13	2011/12
RV price per ton[a]	4502,98	4187,11	5009,92	4738,99	4516,24	4493,04	4555,59
Average yield RV (Tons per hectare)[b]	0,13	0,12	0,09	0,13	0,11	0,12	0,11
Average expected tons/ha[c]	128,00	125,68	120,00	100,00	115,00	100,00	105,00
Income ([a*b*c]*51.25%) * **	37994,35	31878,97	27461,41	32302,13	29545,54	28553,24	26721,10
Allocated Costs							
Total variable costs (TVC)	16364,25	15256,71	13905,27	12523,68	12412,06	10490,11	9840,13
Gross margin (Income-TVC)	21630,10	16622,26	13556,14	19778,45	17133,48	18063,13	16880,97

APPENDIX C. Enterprise budget in a typical year per hectare for popular varieties in Richmond

MPN12	2017/18	2016/17	2015/16	2014/15	2013/14	2012/13	2011/12
RV price per ton[a]	4502,98	4187,11	5009,92	4738,99	4516,24	4493,04	4555,59
Average yield RV (Tons per hectare)[b]	0,12	0,12	0,11	0,11	0,13	0,13	0,13
Average expected tons/ha[c]	128,02	125,00	82,52	64,11	129,36	110,38	100,85

Income (^{a*b*c}*51.25%) ***	35982,37	33285,46	23744,13	17248,70	39897,08	33045,14	31041,94
Allocated Costs							
Cane planting costs-Mechanical land preparation							
Land preparation	3253,00	2824,00	2630,00	2840,00	2583,00	2379,00	2028,00
Hand planting	2770,00	2565,00	2406,00	2793,00	2625,00	2102,00	1880,00
Seedcane	8699,00	6866,00	6158,00	5540,00	5018,00	5139,00	4496,00
Fertiliser and lime	7525,00	7705,00	6884,00	4153,00	4379,00	3576,00	3352,00
Weed control	2677,00	2498,00	2272,00	2522,00	1878,00	1670,00	1425,00
Sundries and contingencies	2493,00	2246,00	2035,00	2677,00	1648,00	1486,00	1318,00
Total cane planting costs^{d}	27417,00	24704,00	22385,00	20525,00	18131,00	16352,00	14499,00
Adjusted planting cost (PC) (^{d}*11.25%) ***	3084,41	2779,20	2518,31	2309,06	2039,74	1839,60	1631,14
Harvesting costs							
Cutting of burnt cane	7523,88	6828,75	4228,58	3050,34	5784,82	3880,92	3020,58
Infield-cane haulage	3236,41	2777,50	1612,54	1378,36	2433,19	1888,58	1649,98
Loading and transhipment of burnt cane	1794,88	1772,50	956,46	833,43	1565,21	1143,52	988,37
Total harvesting costs^{e}	12555,17	11378,75	6797,58	5262,13	9783,23	6913,03	5658,93
Adjusted harvesting cost (HC) (^{e}*52%) ***	6434,52	5831,61	3483,76	2696,84	5013,90	3542,93	2900,20
Ratoon management costs: Dryland cane early harvest							
Field management	528,28	524,37	469,87	433,18	403,69	327,20	307,11
Fertilizer	3233,00	3232,97	3125,82	3042,17	2957,79	2739,20	2586,62
Weed control	2463,00	2486,68	2331,64	2167,17	2009,21	1604,55	1493,59
Sundries and contingencies	622,46	622,46	585,25	565,87	532,93	497,66	434,87
Total ratoon costs^{f}	6847,03	6866,48	6512,59	6208,40	5903,62	5168,61	4822,19
Adjusted ratoon cost (RC) (^{f}*40%) ***	2738,81	2746,59	2605,03	2483,36	2361,45	2067,44	1928,88
Green manuring^{g}		3543,83	3910,82	4020,91	3749,03	3248,71	3018,27
Adjusted green manuring (GM) ^{g}*11.25%) ***	482,84	398,68	439,97	452,35	421,77	365,48	339,56
Eldana control (**E**)	2028,75	2028,75	2028,75	2028,75	2028,75	2028,75	2028,75
Total variable costs (TVC) (PC+HC+RC+GM+E)	14769,34	13784,83	11075,82	9970,37	11865,60	9844,20	8828,52
Gross margin (Income-TVC)	21213,03	19500,62	12668,31	7278,33	28031,48	23200,94	22213,42

MP N31

	2017/18	2016/17	2015/16	2014/15	2013/14	2012/13	2011/12
RV price per ton^{a}	4502,98	4187,11	5009,92	4738,99	4516,24	4493,04	4555,59
Average yield RV (Tons per hectare)^{b}	0,13	0,12	0,11	0,12	0,14	0,14	0,14
Average expected tons/ha^{c}	104,13	100,00	97,53	81,74	85,11	70,85	89,31

Income ([a*b*c]*51.25%) ***	31099,03	26541,02	27470,40	24113,98	26961,10	22124,36	28560,69
Allocated Costs							
Total variable costs (TVC)	12945,73	12478,66	11580,27	10601,27	10048,85	8504,10	8435,59
Gross margin (Income-TVC)	18153,31	14062,36	15890,13	13512,71	16912,25	13620,26	20125,09

FC N48

	2017/18	2016/17	2015/16	2014/15	2013/14	2012/13	2011/12
RV price per ton[a]	4502,98	4187,11	5009,92	4738,99	4516,24	4493,04	4555,59
Average yield RV (Tons per hectare)[b]	0,12	0,13	0,12	0,13	0,13	0,12	0,12
Average expected tons/ha[c]	141,16	125,00	113,03	108,68	116,73	119,00	112,00
Income ([a*b*c]*51.25%) ***	38795,14	33711,75	33757,20	33785,85	34704,49	33040,43	30071,45
Allocated Costs							
Total variable costs (TVC)	15592,31	13920,12	12491,66	11968,48	11493,35	10219,69	9238,89
Gross margin (Income-TVC)	23202,83	19791,63	21265,54	21817,37	23211,13	22820,74	20832,56

FC N54

	2017/18	2016/17	2015/16	2014/15	2013/14	2012/13	2011/12
RV price per ton[a]	4502,98	4187,11	5009,92	4738,99	4516,24	4493,04	4555,59
Average yield RV (Tons per hectare)[b]	0,12	0,13	0,11	0,13	0,12	0,12	0,12
Average expected tons/ha[c]	136,51	153,30	127,00	100,00	123,00	118,00	130,00
Income ([a*b*c]*51.25%) ***	49028,10	53567,23	47465,05	42548,36	46108,62	41532,71	47498,95
Allocated Costs							
Total variable costs (TVC)	18338,88	18323,18	15579,70	13716,64	13979,61	12040,88	11550,79
Gross margin (Income-TVC)	30689,23	35244,04	31885,35	28831,71	32129,01	29491,82	35948,17

MP Energy cane

	2017/18	2016/17	2015/16	2014/15	2013/14	2012/13	2011/12
RV price per ton[a]	4502,98	4187,11	5009,92	4738,99	4516,24	4493,04	4555,59
Average yield RV (Tons per hectare)[b]	0,09	0,08	0,07	0,06	0,07	0,08	0,07
Average expected tons/ha[c]	185,00	150,00	130,00	140,00	160,00	170,00	154,00

Income ([a*b*c]*51.25%) ***	49985,52	33498,55	30395,03	26539,66	33722,96	40738,90	32741,14
Allocated Costs							
Total variable costs (TVC)	21204,52	17840,06	15744,51	15900,73	15837,91	14203,93	12439,57
Gross margin (Income-TVC)	28781,00	15658,50	14650,52	10638,93	17885,06	26534,97	20301,58

SR N50

	2017/18	2016/17	2015/16	2014/15	2013/14	2012/13	2011/12
RV price per ton[a]	4502,98	4187,11	5009,92	4738,99	4516,24	4493,04	4555,59
Average yield RV (Tons per hectare)[b]	0,11	0,13	0,10	0,12	0,12	0,11	0,10
Average expected tons/ha[c]	116,00	145,73	105,00	97,58	125,00	120,00	117,00
Income ([a*b*c]*51.25%) ***	29641,85	39099,83	25914,14	29557,69	34139,97	30948,03	27589,62
Allocated Costs							
Total variable costs (TVC)	15221,03	15600,65	12588,17	11905,02	12311,29	10646,75	9726,25
Gross margin (Income-TVC)	14420,82	23499,18	13325,97	17652,67	21828,68	20301,28	17863,37

FS N52

	2017/18	2016/17	2015/16	2014/15	2013/14	2012/13	2011/12
RV price per ton[a]	4502,98	4187,11	5009,92	4738,99	4516,24	4493,04	4555,59
Average yield RV (Tons per hectare)[b]	0,13	0,11	0,10	0,13	0,11	0,12	0,12
Average expected tons/ha[c]	110,00	108,90	103,00	95,00	105,00	112,20	110,90
Income ([a*b*c]*51.25%) ***	42051,04	33568,43	35346,49	39619,93	35567,19	40331,51	39408,73
Allocated Costs							
Total variable costs (TVC)	18170,22	17026,41	15445,66	14543,08	14207,46	12829,67	11752,81
Gross margin (Income-TVC)	23880,81	16542,02	19900,82	25076,84	21359,73	27501,84	27655,93

FC N37

	2017/18	2016/17	2015/16	2014/15	2013/14	2012/13	2011/12
RV price per ton[a]	4502,98	4187,11	5009,92	4738,99	4516,24	4493,04	4555,59
Average yield RV (Tons per hectare)[b]	0,12	0,13	0,12	0,13	0,14	0,13	0,13
Average expected tons/ha[c]	121,38	115,00	101,45	87,46	109,64	121,03	118,53

Income ([a*b*c]*51.25%) * **	34960,84	31586,39	30804,99	27143,27	35242,51	37001,21	35932,42
Allocated Costs							
Total variable costs (TVC)	14487,52	13350,99	11906,55	10986,54	11134,35	10217,74	9366,60
Gross margin (Income-TVC)	20473,33	18235,40	18898,44	16156,73	24108,17	26783,48	26565,82

FC N35

	2017/18	2016/17	2015/16	2014/15	2013/14	2012/13	2011/12
RV price per ton[a]	4502,98	4187,11	5009,92	4738,99	4516,24	4493,04	4555,59
Average yield RV (Tons per hectare)[b]	0,14	0,13	0,12	0,13	0,14	0,13	0,13
Average expected tons/ha[c]	125,00	131,06	92,00	85,00	92,17	105,51	94,62
Income ([a*b*c]*51.25%) * **	39713,28	35769,02	29227,97	27171,91	29934,80	31065,08	28793,03
Allocated Costs							
Total variable costs (TVC)	14412,05	14067,34	11475,81	10849,13	10424,07	9688,04	8649,34
Gross margin (Income-TVC)	25301,24	21701,68	17752,16	16322,78	19510,72	21377,05	20143,69

FS N54

	2017/18	2016/17	2015/16	2014/15	2013/14	2012/13	2011/12
RV price per ton[a]	4502,98	4187,11	5009,92	4738,99	4516,24	4493,04	4555,59
Average yield RV (Tons per hectare)[b]	0,12	0,13	0,11	0,13	0,12	0,12	0,12
Average expected tons/ha[c]	111,69	125,43	103,91	81,82	100,64	96,55	106,36
Income ([a*b*c]*51.25%) * **	40113,90	43827,73	38835,04	34812,29	37725,24	33981,30	38862,78
Allocated Costs							
Total variable costs (TVC)	15257,52	13820,46	13051,82	12675,18	11860,27	10494,61	9716,59
Gross margin (Income-TVC)	21775,02	30007,27	25783,22	22137,11	25864,97	23486,69	29146,20

SR N37

	2017/18	2016/17	2015/16	2014/15	2013/14	2012/13	2011/12
RV price per ton[a]	4502,98	4187,11	5009,92	4738,99	4516,24	4493,04	4555,59
Average yield RV (Tons per hectare)[b]	0,12	0,13	0,12	0,13	0,14	0,13	0,13
Average expected tons/ha[c]	99,31	94,09	83,01	71,56	89,70	99,03	96,98

Income ($^{[a*b*c]}$*51.25%) ***	28604,33	25843,41	25204,08	22208,13	28834,78	30273,72	29399,25
Allocated Costs							
Total variable costs (TVC)	13378,28	12375,52	11127,85	10317,63	10361,71	9511,38	8746,85
Gross margin (Income-TVC)	15226,04	13467,89	14076,23	11890,50	18473,08	20762,34	20652,40

APPENDIX D Activity and Constraints summary, Mid-Illovo

Activities	
X_1	*Cultivar N12 in marginal poor soil (MPN12)*
X_2	*Cultivar N31 in marginal poor soil (MPN31)*
X_3	*Energy cane in marginal poor soil (MPEC)*
X_4	*Cultivar N12 in flat sandy soil (FSN12)*
X_5	*Cultivar N52 in flat sandy soil (FSN52)*
X_6	*Cultivar N54 in flat sandy soil (FSN54)*

$\boldsymbol{X_{7}}$	*Cultivar N48 in flat clay soil (FCN48)*
$\boldsymbol{X_{8}}$	*Cultivar N12 in flat clay soil (FCN12)*
$\boldsymbol{X_{9}}$	*Cultivar N50 in steep red soil (SRN50)*
$\boldsymbol{X_{10}}$	*Cultivar N54 in steep red soil (SRN54)*
$\boldsymbol{X_{11}}$	*Timber in marginal poor soil (MP Timber)*
$\boldsymbol{X_{12}}$	*Timber in steep red soil (SR Timber)*
$\boldsymbol{X_{13}}$	*Macadamia nuts in flat sandy soil (FSMac)*
$\boldsymbol{X_{14}}$	*Macadamia nuts in flat clay soil (FCMac)*
$\boldsymbol{X_{15}}$	*Sucrose selling*
$\boldsymbol{X_{16}}$	*Molasses selling*
$\boldsymbol{X_{17}}$	*Bagasse selling*
$\boldsymbol{X_{18}}$	*Expected Gross Margin (Rands)*
Gross margin deviations (risk)	
$\boldsymbol{X_{19}}$	*D1 (Deviation in time period 1in Rands)*
$\boldsymbol{X_{20}}$	*D2 (Deviation in time period 2 in Rands)*
$\boldsymbol{X_{21}}$	*D3(Deviation in time period 3 in Rands)*
$\boldsymbol{X_{22}}$	*D4 (Deviation in time period 4 in Rands)*
$\boldsymbol{X_{23}}$	*D5 (Deviation in time period 5 in Rands)*
$\boldsymbol{X_{24}}$	*D6 (Deviation in time period 6 in Rands)*
$\boldsymbol{X_{25}}$	*D7 (Deviation in time period 7 in Rands)*
$\boldsymbol{X_{26}}$	*0.5TAD (Total absolute deviations)*
$\boldsymbol{X_{27}}$	*Standard deviation*
Constraints	
B_{1}	*Marginal poor soil*
B_{2}	*Flat land sandy soil*
B_{3}	*Flat land clay soil*
B_{4}	*Sucrose transfer*
B_{5}	*Molasses transfer*
B_{6}	*Bagasse transfer*
B_{7}	*Macadamia nut constraint*
B_{8}	*Cultivar N12 constraint*
B_{9}	*Energy cane constraint*
B_{10}	*Cultivar N31 constraint*
B_{11}	*Cultivar N54 constraint*
B_{12}	*Cultivar N48 constraint*
B_{13}	*Cultivar N50 constraint*
Time periods (risk)	
B_{15}	*Deviation in Time period 1 (T1)*
B_{16}	*Deviation in Time period 1 (T2)*
B_{17}	*Deviation in Time period 1 (T3)*
B_{18}	*Deviation in Time period 1 (T4)*
B_{19}	*Deviation in Time period 1 (T5)*
B_{20}	*Deviation in Time period 1 (T6)*
B_{21}	*Deviation in Time period 1 (T7)*
Mid-Illovo objective function $\boldsymbol{X_{18} - 1.645X_{27}}$ **Where X_{18} is the expected gross margin E[GM] and X_{27} is the standard deviation**	

E[GM] equation for Mid-Illovo

$$-13737.4X_1 - 12628.8X_2 - 22163.1X_3 - 14602.9X_4 - 16364.3X_5 - 17075.1X_6 - 15623.1X_7 - 13579.4X_8 - 15986.3X_9 - 15925.9X_{10} + 3428X_{11} + 3428X_{12} + 20793X_{13} + 46888X_{14} + 3200X_{15} + 1000X_{16} + 500X_{17} - X_{18} = 0$$

APPENDIX E Activity and Constraint summary Richmond

Activities	
X_1	*Cultivar N12 in marginal poor soil (MPN12)*
X_2	*Cultivar N31 in marginal poor soil (MPN31)*
X_3	*Energy cane in marginal poor soil (MPEC)*
X_4	*Cultivar N52 flat sandy soil (FSN52)*
X_5	*Cultivar N54 in flat sandy soil (FSN54)*
X_6	*Cultivar N37 in flat clay soil (FCN37)*
X_7	*Cultivar N48 in flat clay soil (FCN48)*
X_8	*Cultivar N54 in flat clay soil (FCN54)*
X_9	*Cultivar N35 in flat clay soil (FC35)*
X_{10}	*Cultivar N50 in steep red soil (SRN50)*
X_{11}	*Cultivar N37 in steep red soil (SRN37)*
X_{12}	*Cultivar N48 in flat clay soil (SRN48)*
X_{13}	*Timber in marginal poor soil (MPTimber)*
X_{14}	*Timber in steep red soil (SRTimber)*
X_{15}	*Macadamia nuts in flat sandy soil (FSMac)*
X_{16}	*Macadamia nuts in flat clay soil (FCMac)*
X_{17}	*Sucrose selling*
X_{18}	*Molasses selling*
X_{19}	*Bagasse selling*
X_{20}	*Expected Gross Margin (Rands)*
***Gross margin deviations* (*risk*)**	
X_{21}	*D1 (Deviation in time period 1in Rands)*
X_{22}	*D2 (Deviation in time period 2 in Rands)*
X_{23}	*D3(Deviation in time period 3 in Rands)*
X_{24}	*D4 (Deviation in time period 4 in Rands)*
X_{25}	*D5 (Deviation in time period 5 in Rands)*
X_{26}	*D6 (Deviation in time period 6 in Rands)*
X_{27}	*D7 (Deviation in time period 7 in Rands)*
X_{28}	*0.5TAD (Total absolute deviations)*
X_{29}	*Standard deviation*
Constraints	
B_1	*Marginal poor soil*
B_2	*Flat land sandy soil*
B_3	*Flat land clay soil*
B_4	*Sucrose transfer*
B_5	*Molasses transfer*
B_6	*Bagasse transfer*
B_7	*Macadamia nut constraint*
B_8	*Cultivar N12 constraint*
B_9	*Energy cane constraint*
B_{10}	*Cultivar N31 constraint*
B_{11}	*Cultivar N54 constraint*
B_{12}	*Cultivar N48 constraint*
B_{13}	*Cultivar N50 constraint*
Time periods (risk)	
B_{15}	*Deviation in Time period 1 (T1)*

B_{16}	*Deviation in Time period 1 (T2)*
B_{17}	*Deviation in Time period 1 (T3)*
B_{18}	*Deviation in Time period 1 (T4)*
B_{19}	*Deviation in Time period 1 (T5)*
B_{20}	*Deviation in Time period 1 (T6)*
B_{21}	*Deviation in Time period 1 (T7)*

Richmond objective function

$$\boldsymbol{X_{20} - 1.086X_{29}}$$

Where X_{20} is the expected gross margin E[GM] and X_{29} is the standard deviation

E[GM] equation for Richmond

$$\begin{aligned}-14769.3X_1 - 12945.7X_2 - 21204.5X_3 - 18170.2X_4 - 15257.5X_5 - 14487.5X_6 \\ - 15592.3X_7 - 18338.9X_8 - 14412.1X_9 - 15221X_{10} - 13378.3X_{11} \\ - 15592.3X_{12} + 3428X_{13} + 3428X_{14} + 20793X_{15} + 17262X_{16} \\ + 3200X_{17} + 1000X_{18} + 500X_{19} - X_{20} = 0\end{aligned}$$

APPENDIX F An outline of all the activities of the integrated model

Activities (let Xi denote an activity, Merged model)			
Index	**Definition**	**Index**	**Definition**
X_{1}	Cultivar N12 in marginal poor soil (MPN12)	X_{20}	Bagasse EC
X_{2}	Energy cane in marginal poor soil (MP Energy Cane)	X_{21}	E[GM] (Rands)
X_{3}	Cultivar N31 in marginal poor soil (MPN31)	**Gross margin deviations (Di) in Rands**	
X_{4}	Cultivar N31 in flat sandy soil (FSN31)	X_{22}	D1 (Deviation in time period 1)
X_{5}	Cultivar N54 in flat sandy soil (FSN54)	X_{23}	D2 (Deviation in time period 2)
X_{6}	Cultivar N48 in flat sandy soil (FCN48)	X_{24}	D3(Deviation in time period 3)
X_{7}	Cultivar N50 in flat clay soil (FCN50)	X_{25}	D4 (Deviation in time period 4)
X_{8}	Timber in marginal poor soil (MPTimber)	X_{26}	D5 (Deviation in time period 5)
X_{9}	Macadamia nuts in flat sandy soil (FSMac)	X_{27}	D6 (Deviation in time period 6)
X_{10}	Macadamia nuts in flat sandy soil (FCMac)	X_{28}	D7 (Deviation in time period 7)
X_{11}	Burning with topping	X_{29}	0.5TAD (Total absolute deviations)
X_{12}	Green harvesting without topping	X_{30}	SD (Standard deviation Rands)
X_{13}	Sugarcane tons harvested EC	X_{31}	GM Eston Central
X_{14}	Sugarcane tons harvested CC	**Mid-Illovo**	
X_{15}	Sucrose CC	X_{32}	Cultivar N12 in marginal poor soil (MPN12)
X_{16}	Sucrose EC	X_{33}	Energy cane in marginal poor soil (MP Energy Cane)
X_{17}	Molasses CC	X_{34}	Cultivar N31 in marginal poor soil (MPN31)
X_{18}	Molasses EC	X_{35}	Cultivar N12 in flat sandy soil (FSN12)
X_{19}	Baggase CC	X_{36}	Cultivar N52 in flat sandy soil (FSN52)

Activities (let Xi denote an activity, Merged model)			
Index	**Definition**	**Index**	**Definition**
X_{37}	FCN54	X_{56}	E[GM] (Rands)
X_{38}	FCN48	**Gross margin deviations (Di) in Rands**	
X_{39}	FCN12	X_{57}	D1 (Deviation in time period 1)
X_{40}	SRN50	X_{58}	D2 (Deviation in time period 2)
X_{41}	SRN54	X_{59}	D3(Deviation in time period 3)
X_{42}	MPTimber	X_{60}	D4 (Deviation in time period 4)
X_{43}	SR Timber	X_{61}	D5 (Deviation in time period 5)
X_{44}	FSMac	X_{62}	D6 (Deviation in time period 6)
X_{45}	FCMac	X_{63}	D7 (Deviation in time period 7)
X_{46}	Burning with topping	X_{64}	0.5TAD (Total absolute deviations)
X_{47}	Green harvesting without topping	X_{65}	SD (Standard deviation Rands)
X_{48}	Sugarcane tons harvested EC	X_{66}	GM Mid-Illovo
X_{49}	Sugarcane tons harvested CC	**Richmond**	
X_{50}	Sucrose CC	X_{67}	MPN12
X_{51}	Sucrose EC	X_{68}	MPN31
X_{52}	Molasses CC	X_{69}	MP Energy Cane
X_{53}	Molasses EC	X_{70}	FSN52
X_{54}	Baggase CC	X_{71}	FSN54
X_{55}	Bagasse EC	X_{72}	FCN37

Activities (let Xi denote an activity, Merged model)

Index	***Definition***	***Index***	***Definition***
X_{73}	*FCN48*	X_{92}	*Bagasse EC*
X_{74}	*FCN54*	X_{93}	*E[GM] (Rands)*
X_{75}	*FCN35*	***Gross margin deviations (Di) in Rands***	
X_{76}	*SRN50*	X_{94}	*D1(Rands)*
X_{77}	*SRN37*	X_{95}	*D2 (Rands)*
X_{78}	*SRN48*	X_{96}	*D3(Rands)*
X_{79}	*MPTimber*	X_{97}	*D4 (Rands)*
X_{80}	*SR Timber*	X_{98}	*D5 (Rands)*
X_{81}	*FSMac*	X_{99}	*D6 (Rands)*
X_{82}	*FCMac*	X_{100}	*D7 (Rands)*
X_{83}	*Burning with topping*	X_{101}	*0.5TAD*
X_{84}	*Green harvesting without topping*	X_{102}	*SD (Rands)*
X_{85}	*Sugarcane tons harvested EC*	X_{103}	*GM Rich*
X_{86}	*Sugarcane tons harvested CC*	***Summing up raw material supply from all three farm models***	
X_{87}	*Sucrose CC*	X_{104}	*Total (tons) sugarcane CC*
X_{88}	*Sucrose EC*	X_{105}	*Total (tons) sugarcane EC*
X_{89}	*Molasses CC*	X_{106}	*Baggasse CC*
X_{90}	*Molasses EC*	X_{107}	*Bagasse EC*
X_{91}	*Baggase CC*	X_{108}	*Sucrose CC*

Activities (let Xi denote an activity, Merged model)			
Index	***Definition***	***Index***	***Definition***
X_{109}	*Sucrose EC*	X_{127}	*Int Boiler B*
X_{110}	*Molasses CC*	X_{128}	*Electricity total cane crushed*
X_{111}	*Molasses EC*	X_{129}	*Surplus Electricity*
The Biorefinery appended to the mill		X_{130}	*Excess bagg*
X_{112}	*CC Cane crushing*	X_{131}	*Storage*
X_{113}	*EC Cane crushing*	X_{132}	*INT BRFP 1 Investment*
X_{114}	*EC+CC Cane crushing tons*	X_{133}	*Bagg to BRFP 1 pdtn/Methanol*
X_{115}	*EC bagg mill*	X_{134}	*BRFP 1 quantity sold*
X_{116}	*CC bagg mill*	X_{135}	*BRFP1 millions*
X_{117}	*Tons Bagg EC+CC*	X_{136}	*INT BRFP 2/ Bio-ethanol*
X_{118}	*EC molasses in mill*	X_{137}	*EC+CC Clear juice tons*
X_{119}	*CC molasses in mill*	X_{138}	*CJ to BRFP2 pdtn/Bio-ethanol*
X_{120}	*Tons EC+CC molasses*	X_{139}	*BFRP 2 quantity sold*
X_{121}	*EC suc in mill*	X_{140}	*BRFP2 produced*
X_{122}	*CC suc in mill*	X_{141}	*CJ toEvaporating pan*
X_{123}	*Tons suc EC+CC*	X_{142}	*INT BRF3 invstmt*
X_{124}	*tons bagasse boiler A*	X_{143}	*Tons syrup produced*
X_{125}	*Int Boiler A*	X_{144}	*Syr to BRFP3 pdtn/Lysine*
X_{126}	*tons bagasse boiler B*	X_{145}	*BRFP3 quantity sold*

Activities (let Xi denote an activity, Merged model)			
Index	***Definition***	***Index***	***Definition***
X_{146}	*BRFP3 in millions*	***Methanol domestic demand segments***	
X_{147}	*Syrup to A Sugar & Amol*	X_{163}	*1*
X_{148}	*tons molasses*	X_{164}	*2*
X_{149}	*tons sugar*	X_{165}	*3*
X_{150}	*Total Sugar quantiy*	X_{166}	*4*
X_{151}	*Sugar in millions*	X_{167}	*5*
Sugar domestic demand segments		*Lysine domestic demand*	
X_{152}	*1*	X_{168}	*1*
X_{153}	*2*		
X_{154}	*3*		
X_{155}	*4*		
X_{156}	*5*		
X_{157}	*EXPORT SEGMENT*		
Ethanol domestic demand segments			
X_{158}	*1*		
X_{159}	*2*		
X_{160}	*3*		
X_{161}	*4*		
X_{162}	*5*		

APPENDIX G An outline of all the constraints of the integrated model

Constraints for the combined model (let Bi denote constraint)			
Index	***Definition***	***Index***	***Definition***
B_1	*Marginal Poor Soil (MP)*	*Deviations in Time periods (T_i)*	
B_2	*Flat land Sandy soil (FS)*	B_{20}	*Deviation in Time period 1 (T1)*
B_3	*Flat land Clay soil (FC)*	B_{21}	*Deviation in Time period 2 (T2)*
B_4	*Harvesting (ha)*	B_{22}	*Deviation in time period 3 (T3)*
B_5	*Sugarcane transfer CC (tons/ha)*	B_{23}	*Deviation in time period 4(T4)*
B_6	*Sugarcane transfer EC (tons/ha)*	B_{24}	*Deviation in time period (T5)*
B_7	*Sucrose transfer CC (tons/ha)*	B_{25}	*Deviation in time period (T6)*
B_8	*Sucrose transfer EC (tons/ha)*	B_{26}	*Deviation in time period (T7)*
B_9	*Molasses transfer CC (tons/ha)*	B_{27}	*Sum (Rands)*
B_{10}	*Molasses transfer EC (tons/ha)*	B_{28}	*Conv (Rands)*
B_{11}	*Bagasse transfer CC (tons/ha)*	B_{29}	*E[GM] Acc Constraint*
B_{12}	*Bagasse transfer EC (tons/ha)*	B_{30}	$L= E[GM]-\theta\sigma$
B_{13}	*Macadamia constraint*	***Mid-Illovo***	
B_{14}	*N12 constraint*	$\mathbf{B_{31}}$	*Marginal Poor Soil (MP)*
B_{15}	*Energy cane constraint*	B_{32}	*Flat land Sandy soil (FS)*
B_{16}	*N31 constraint*	B_{33}	*Flat land Clay soil (FC)*
B_{17}	*N54 constraint*	B_{34}	*Steep red soil (SR)*
B_{18}	*N48 constraint*	B_{35}	*Harvesting (ha)*
B_{19}	*N50 constraint*	B_{36}	*Sugarcane transfer CC (tons/ha)*

Constraints for the combined model (let Bi denote constraint)			
Index	**Definition**	**Index**	**Definition**
B_{37}	*Sugarcane transfer EC (tons/ha)*	B_{55}	*Deviation in time period 4(T4)*
B_{38}	*Sucrose transfer CC (tons/ha)*	B_{56}	*Deviation in time period (T5)*
B_{39}	*Sucrose transfer EC (tons/ha)*	B_{57}	*Deviation in time period (T6)*
B_{40}	*Molasses transfer CC (tons/ha)*	B_{58}	*Deviation in time period (T7)*
B_{41}	*Molasses transfer EC (tons/ha)*	B_{59}	*Sum (Rands)*
B_{42}	*Bagasse transfer CC (tons/ha)*	B_{60}	*Conv (Rands)*
B_{43}	*Bagasse transfer EC (tons/ha)*	B_{61}	*E[GM] Acc Constraint*
B_{44}	*Macadamia constraint*	B_{62}	$L = E[GM] - \theta\sigma$
B_{45}	*N12 constraint*	***Richmond***	
B_{46}	*N31 constraint*	B_{63}	*Marginal Poor Soil (MP)*
B_{47}	*Energy Cane constraint*	B_{64}	*Flat land Sandy soil (FS)*
B_{48}	*N52 constraint*	B_{65}	*Flat land Clay soil (FC)*
B_{49}	*N54 constraint*	B_{66}	*Steep land Red soil (SR)*
B_{50}	*N48 constraint*	B_{67}	*Harvesting (ha)*
B_{51}	*N50 constraint*	B_{68}	*Sugarcane transfer CC (tons/ha)*
Deviations in Time periods (T_i)		B_{69}	*Sugarcane transfer EC*
B_{52}	*Deviation in Time period 1 (T1)*	B_{70}	*Sucrose transfer CC (tons/ha)*
B_{53}	*Deviation in Time period 2 (T2)*	B_{71}	*Sucrose transfer EC (tons/ha)*
B_{54}	*Deviation in time period 3 (T3)*	B_{72}	*Molasses transfer CC (tons/ha)*

Constraints for the combined model (let Bi denote constraint)

Index	Definition	Index	Definition
B_{73}	Molasses transfer EC (tons/ha)	B_{91}	Deviation in time period (T6)
B_{74}	Bagasse transfer CC (tons/ha)	B_{92}	Deviation in time period (T7)
B_{75}	Bagasse transfer EC (tons/ha)	B_{93}	Sum (Rands)
B_{76}	Macadamia constraint	B_{94}	Conv (Rands)
B_{77}	N12 constraint	B_{95}	E[GM] Acc Constraint
B_{78}	N31 constraint	B_{96}	$L= E[GM]-\theta\sigma$
B_{79}	Energy Cane constraint	B_{97}	Sum Cane Supply CC
B_{80}	N52 constraint	B_{98}	Sum Cane Supply EC
B_{81}	N54 constraint	B_{99}	Sum Sucrose Supply CC
B_{82}	N37 constraint	B_{100}	Sum Sucrose Supply EC
B_{83}	N48 constraint	B_{101}	Sum Molasses Supply CC
B_{84}	N35 constraint	B_{102}	Sum Molasses Supply EC
B_{85}	N50 constraint	B_{103}	Sum Bagasse Supply CC
Deviations in Time periods (T_i)		B_{104}	Sum Bagasse Supply EC
B_{86}	Deviation in Time period 1 (T1)	**BAM Model constraints**	
B_{87}	Deviation in Time period 2 (T2)	B_{105}	CC supplied
B_{88}	Deviation in time period 3 (T3)	B_{106}	EC supplied
B_{89}	Deviation in time period 4(T4)	B_{107}	tons of CC bagg supplied
B_{90}	Deviation in time period (T5)	B_{108}	tons of EC bagg supplied

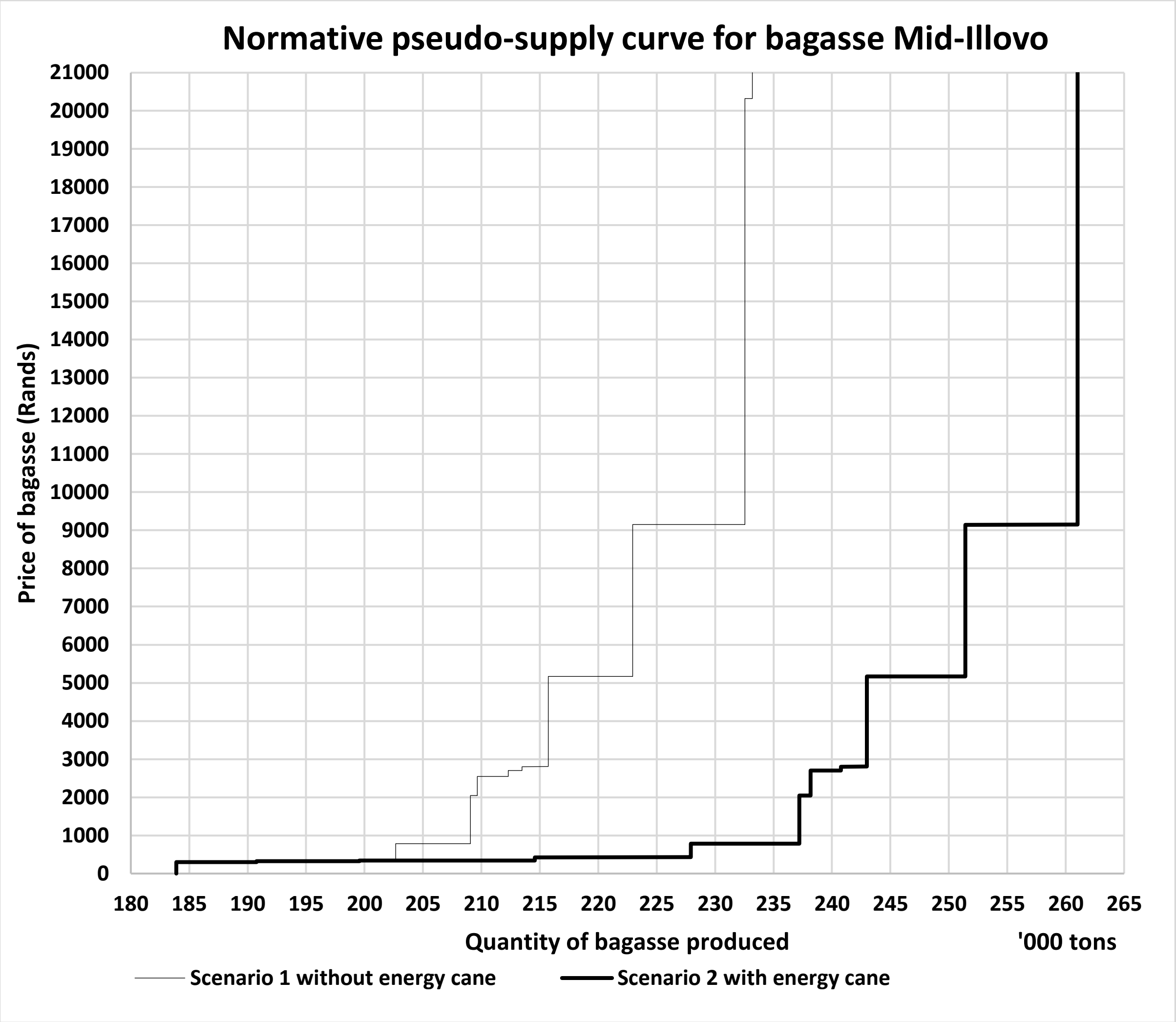
Constraints for the combined model (let Bi denote constraint)

Index	***Definition***	***Index***	***Definition***
B_{109}	*CC sucrose supplied*	B_{127}	*BRFP1 conversion factor*
B_{110}	*EC sucrose supplied*	B_{128}	*clear juice tons in the mill*
B_{111}	*CC molasses supplied*	B_{129}	*clear juice tons transfer*
B_{112}	*EC molasses supplied*	B_{130}	*BRFP2 capacity*
B_{113}	*Cane Crushing tons EC+CC*	B_{131}	*BRFP 2 produced/ton r.m*
B_{114}	*Bagg EC+CC tons*	B_{132}	*BRFP2 conversion factor*
B_{115}	*CC+EC suc tons*	B_{133}	*Syrup tr*
B_{116}	*CC+EC molassses tons*	B_{134}	*Syrup to A mol and A sugar*
B_{117}	*Bagg to the boiler*	B_{135}	*Tons molasses produced*
B_{118}	*Boiler A*	B_{136}	*Total tons molasses produced in mill*
B_{119}	*Boiler B*	B_{137}	*BRFP3capacity*
B_{120}	*Boiler choice*	B_{138}	*BRFP3 produced/ton r.m*
B_{121}	*Electricity supply Boiler (KWh)*	B_{139}	*BRFP3 conversion factor*
B_{122}	*Electricity demand (tons) (KWh)*	B_{140}	*Tons sugar from syrup*
B_{123}	*Excess bagg*	B_{141}	*Total sugar produced*
B_{124}	*Excess bagg transfer*	B_{142}	*Sugar conversion factor*
B_{125}	*BRFP1 capacity*	B_{143}	*SS&DD sugar*
B_{126}	*BRFP1 produced/ton r.m*	B_{144}	*SS&DD ethanol*

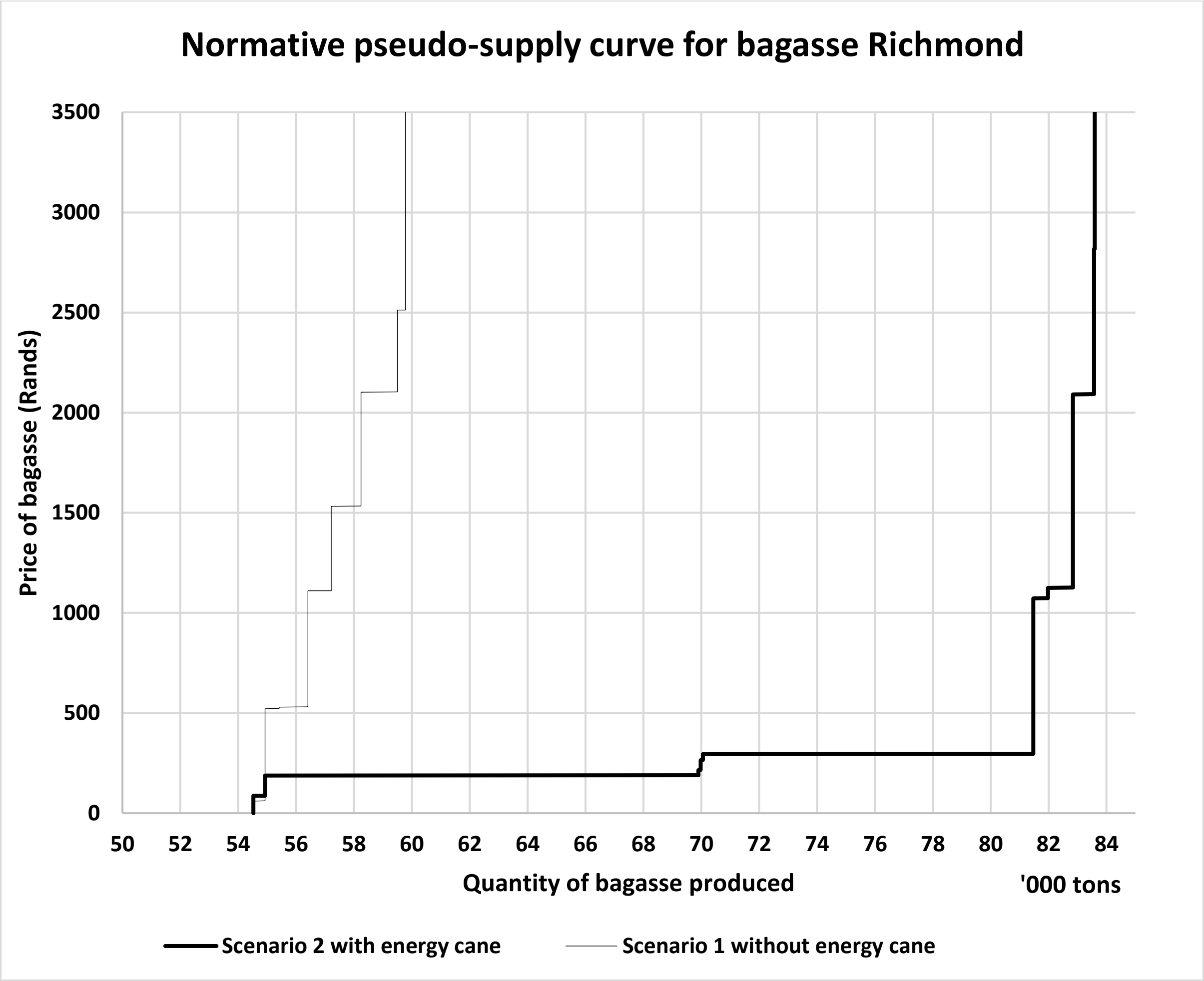
Constraints for the combined model (let Bi denote constraint)

Index	***Definition***	***Index***	***Definition***
X_{145}	*SS&DD methanol*	X_{148}	*Domestic CC lysine*
X_{146}	*SS&DD lysine*	X_{149}	*Domestic CC sugar*
X_{147}	*Domestic CC methanol*	X_{150}	*Domestic CC ethanol*

APPENDIX H Pseudo-supply curves for Mid-Illovo and Richmond



A normative pseudo-supply curve for bagasse under two scenarios for Mid-Illovo



A normative pseudo-supply curve for bagasse under two scenarios for Richmond

APPENDIX I Variations in area under cane, variety selection and enterprise selection at different bagasse prices

Distribution of area under cane and opportunity cost of land at different bagasse prices per ton for S1 and S2 (Mid-Illovo)

Bagasse price (Rands	**Percentage area planted in hectares out of total arable land**													
Scenario 1 (Without Energy Cane)														
	MP N12	**MP N31**	**MP Energy Cane**	**FS N12**	**FS N52**	**FC N54**	**FC N48**	**FC N12**	**SR N50**	**SR N54**	**MP Timber**	**SR Timber**	**FS Mac**	**FC Mac**
0	3	4	0	2	0	0	33	20	0	23	0	0	6	9
303	4	3	0	3	0	10	33	10	0	23	0	0	5	10
327	2	4	0	8	0	10	33	9	0	23	0	0	0	11
355	6	0	0	8	0	10	33	10	0	23	0	0	0	10
782	6	0	0	8	0	10	33	13	0	23	0	0	0	7
2048	6	0	0	8	0	10	28	19	0	23	0	0	0	6
2548	6	0	0	8	0	10	30	19	0	23	0	0	0	4
2699	6	0	0	8	0	10	33	16	0	23	0	0	0	4
2804	6	0	0	0	8	10	33	16	0	23	0	0	0	4
5166	6	0	0	0	8	10	33	20	0	23	0	0	0	0
9149	6	0	0	0	8	30	33	0	20	3	0	0	0	0
20325	6	0	0	0	8	33	30	0	23	0	0	0	0	0
Scenario 2 (With Energy Cane)														
0	3	4	0	2	0	0	33	20	0	23	0	0	6	9
303	4	3	0	3	0	10	33	10	0	23	0	0	5	10
327	2	4	0	8	0	10	33	9	0	23	0	0	0	11
341	3	0	3	8	0	10	33	8	0	23	0	0	0	12
427	0	0	6	8	0	10	33	8	0	23	0	0	0	12

782	0	0	6	8	0	10	33	13	0	23	0	0	0	7
2048	0	0	6	8	0	10	26	22	0	23	0	0	0	5
2699	0	0	6	8	0	10	33	15	0	23	0	0	0	5
2804	0	0	6	0	8	10	33	16	0	23	0	0	0	4
5166	0	0	6	0	8	10	33	20	0	23	0	0	0	0
9148	0	0	6	0	8	30	33	0	20	3	0	0	0	0

Distribution of area under cane and opportunity cost of land at different bagasse prices per ton for S1 and S2 (Richmond)

Bagasse price (Rands	**Percentage area planted in hectares out of total arable land**															
Scenario 1(Without energy cane)																
	MP N12	**MP N31**	**MP Energy Cane**	**FS N52**	**FS N54**	**FC N37**	**FC N48**	**FC N54**	**FC N35**	**SR N50**	**SR N37**	**SR N48**	**MP Timber**	**SR Timber**	**FS Mac**	**FC Mac**
0	10	13	0	0	15	0	32	0	0	0	24	1	0	0	4	0
62	8	15	0	0	16	0	32	0	0	0	24	1	0	0	3	0
523	10	14	0	0	16	0	25	6	0	0	18	8	0	0	3	0
531	24	0	0	0	16	0	29	3	0	0	21	4	0	0	3	0
1111	24	0	0	0	17	0	23	8	0	0	16	10	0	0	2	0
1533	24	0	0	0	18	0	8	9	16	0	0	25	0	0	1	0
2103	24	0	0	0	19	0	8	24	0	0	0	25	0	0	0	0
2513	24	0	0	0	19	0	8	24	0	0	0	25	0	0	0	0
3000	24	0	0	0	19	0	8	24	0	0	0	25	0	0	0	0
Scenario 2 (With energy cane)																
0	**10**	13	0	0	15	0	32	0	0	0	24	1	0	0	4	0

88	**8**	15	0	0	16	0	32	0	0	0	24	1	0	0	3	0
189	**10**	0	13	0	16	0	32	0	0	0	24	1	0	0	3	0
217	**11**	0	13	0	16	0	32	0	0	0	24	1	0	0	3	0
266	**11**	0	13	0	16	0	31	0	0	0	24	2	0	0	3	0
296	**0**	0	24	0	17	0	25	7	0	0	17	8	0	0	3	0
1074	**0**	0	24	0	16	0	15	17	0	0	8	18	0	0	3	0
1126	**0**	0	24	0	18	0	17	15	0	0	9	16	0	0	1	0
2092	**0**	0	24	0	19	0	18	14	0	0	10	15	0	0	0	0
2818	**0**	0	24	0	19	0	8	14	10	0	0	25	0	0	0	0

APPENDIX J Percentage changes in quantities of bagasse produced and revenue at different bagasse prices for Mid-Illovo and Richmond

Percentage change in quantity produced and revenue with each change in bagasse price (Mid-Illovo)

Scenario 1: Without energy cane		
Bagasse price per ton (Rands)	**Cumulative percentage increase in quantity of bagasse produced**	**Marginal percentage change in revenue for growers**
0	0	0
303	4	25
327	9	2
355	10	2
782	14	30
2048	14	70
2548	15	16
2699	16	4
2804	17	3
5166	21	63
9149	26	68
20325	27	118
Scenario 2: With energy cane		
0	0	0
303	4	25
327	9	2
341	17	1
427	24	6
782	29	26
2048	30	77
2699	31	23
2804	32	3
5166	37	66
9148	42	69

Percentage change in quantity produced and revenue with each change in bagasse price (Richmond)

Scenario 1: Without EC		
Bagasse price per ton (Rands)	**Cumulative percentage increase in quantity of bagasse produced**	**Marginal percentage change in revenue for growers**
0	0	0
62	1	10
523	2	69

531	3	1
1111	5	53
1533	7	25
2103	9	28
2513	10	16
3000	10	16
Scenario 2: With EC		
0	0	0
88	1	15
189	28	15
217	28	5
266	28	8
296	49	4
1074	50	128
1126	52	4
2092	53	68
2818	53	31

APPENDIX K An outline of changes in sucrose, molasses and bagasse quantities delivered to the mill at different bagasse price levels per ton for S1 and S2.

Mid-Illovo	**Quantities delivered in tons**		
Bagasse Price	**Sucrose**	**Molasses**	**Fibre**
Scenario 1 (without energy cane)			
0	79686,67	24518,98	183892,32
303	82664,79	25435,32	190764,91
327	86475,22	26607,76	199558,19
355	87817,89	27020,89	202656,68
782	90588,83	27873,49	209051,15
2048	90850,33	27953,95	209654,62
2548	91997,33	28306,87	212301,54
2699	92511,09	28464,95	213487,14
2804	93477,76	28762,39	215717,90
5166	96610,30	29726,25	222946,86
9149	100769,61	31006,03	232545,25
20325	101047,12	31091,42	233185,67
Scenario 2 (with energy cane)			
0	79686,67	24518,98	183892,32
303	82664,79	25435,32	190764,91
327	86475,22	26607,76	199558,19
341	86839,47	25848,02	214582,07
427	87140,75	25163,31	227924,82
782	91159,01	26399,70	237197,72
2048	91583,50	26530,31	238177,30
2699	92705,64	26875,58	240766,86
2804	93672,30	27173,02	242997,62
5166	97321,67	28295,90	251419,24
9148	101480,98	29575,68	261017,64

Richmond	**Quantities delivered in tons**		
Scenario 1 (without energy cane)			
Bagasse Price	**Sucrose**	**Molasses**	**Fibre**
0	23627,48	7270,00	54524,94
62	23802,55	7323,86	54928,96
523	24013,18	7388,67	55415,03
531	24442,28	7520,70	56405,27
1111	24792,79	7628,55	57214,13
1533	25238,89	7765,81	58243,6
2103	25782,83	7933,18	59498,83
2513	25903,98	7970,45	59778,41
3000	25903,98	7970,45	59778,41
Scenario 2 (with energy cane)			
0	23627,48	7270,00	54524,94
88	23802,55	7323,86	54928,96
189	24712,47	6812,65	69900,33
217	24708,96	6806,19	69979,8
266	24730,23	6811,11	70055,32
296	25167,76	6306,00	81472,52
1074	25387,67	6373,67	81980,02
1126	25760,29	6488,32	82839,9
2092	26076,18	6585,52	83568,87
2818	26088,53	6589,32	83597,38

APPENDIX L An annualised budget for 2018 mature timber

	2018
Price (Pulp)[a]	750,47
Price (Poles)[b]	881,80
Yield Pulp[c]	5,00
Yield Poles[d]	15,00
Gross Income$^{(a*c) +(b*d)}$	16 979,35
Establishment costs	8 838,56
Maintenance Costs	310,40
Harvesting costs	4 503,29
Total costs (maintenance+harvesting+establishment)	13 652
Gross margin (Gross Income-Total costs)	3 327,35

Gum Pole yield is 120 tons per hectare at maturity, matures after 8 years therefore 15 tons are harvested per year. Likewise, 40 tons of pulp are harvested at maturity, therefore 5 tons are harvested per year.

** Annually the land allocated to planting, harvesting and maintenance is indicated below. The gross income and costs were adjusted according to these percentages in the budgets

13%- planting
13%- harvesting
100%- maintanance

APPENDIX M Macadamia budget 2018 for trees in year 6 of maturity

	Sandy soils	**Clay soils**
Yields (tons/ha) (sandy soils)[a]	1,10	
Yields (tons/ha) (clay soils)[b]		1,40
Price (R/kg)[c]	80,00	80,00
Gross income [a*c or b*c]	88 000,00	112 000,00
Gross total Costs (land prep, irrigation, labour, herbicides and machinery/ha	65 996,78	81 635,68
Gross margin/ha	22 003,22	30 364,32

**It is important to note that as the trees mature, yields increase and so do costs. At year 10 and beyond, the trees can consistently yield 3,12 tons of macadamias per hectare. The rate at which costs increase is much lower than the rate at which yields and overall productivity of the trees increase, leading to very high profits.

The area planted, maintained, harvested and destumped per year is adjusted according to the percentages below. This was taken note of in the budgets.

Planting	3%
Maintenance	100%
Harvesting	90%
Destumping	3%

APPENDIX N Matrix for the BAM model

	CC tons supplied	EC tons supplied	CC bagasse tons supplied	EC bagasse tons suppli	CC sucrose tons supplied	EC sucrose tons supplied	CC molasses tons supp
CC supplied	-1						
EC supplied		-1					
tons of CC bagg supplied			-1				
tons of EC bagg supplied				-1			
CC sucrose supplied					-1		
EC sucrose supplied						-1	
CC molasses supplied							-1
EC molasses supplied							
Cane Crushing tons EC+CC							
Bagg EC+CC tons							
CC+EC suc tons							
CC+EC molassses tons							
Bagg to the boiler							
Boiler A							
Boiler B							
Boiler choice							
Electricity supply Boiler (MWh)							
Electricity demand (tons) (MWh)							
Excess bagg							
Excess bagg transfer							
BRFP1 capacity							
BRFP1 produced/ton r.m							
BRFP1 conversion factor							
clear juice tons in the mill							
clear juice tons transfer							
BRFP2 capacity							
BRFP 2 produced/ton r.m							
BRFP2 conversion factor							
Syrup tr							
Syrup to A mol and A sugar							
Tons molasses produced							
Total tons molasses produced in mill							
BRFP3capacity							
BRFP3 produced/ton r.m							
BRFP3 conversion factor							
Tons sugar from syrup							
Total sugar produced							
Sugar conversion factor							
SS&DD sugar							
SS&DD ethanol							
SS&DD methanol							
SS&DD lysine							
Domestic CC methanol							
Domestic CC lysine							
Domestic CC sugar							
Domestic CC ethanol							
Objective function							

	EC molasses tons supplied	CC Cane crushing	EC Cane crushing	EC+CC Cane crushing tons	EC bagg mill	CC bagg mill	Tons Bagg EC+CC	EC molasses in mill	CC molasses in mill
CC supplied		1							
EC supplied			1						
tons of CC bagg supplied						1			
tons of EC bagg supplied					1				
CC sucrose supplied									
EC sucrose supplied									
CC molasses supplied									1
EC molasses supplied	-1							1	
Cane Crushing tons EC+CC		-1	1	1					
Bagg EC+CC tons					-1	1	1		
CC+EC suc tons									
CC+EC molassses tons								-1	1
Bagg to the boiler							-1		
Boiler A									
Boiler B									
Boiler choice									
Electricity supply Boiler (MWh)									
Electricity demand (tons) (MWh)				-0,032					
Excess bagg							1		
Excess bagg transfer									
BRFP1 capacity									
BRFP1 produced/ton r.m									
BRFP1 conversion factor									
clear juice tons in the mill									
clear juice tons transfer									
BRFP2 capacity									
BRFP 2 produced/ton r.m									
BRFP2 conversion factor									
Syrup tr									
Syrup to A mol and A sugar									
Tons molasses produced									
Total tons molasses produced in mill									
BRFP3capacity									
BRFP3 produced/ton r.m									
BRFP3 conversion factor									
Tons sugar from syrup									
Total sugar produced									
Sugar conversion factor									
SS&DD sugar									
SS&DD ethanol									
SS&DD methanol									
SS&DD lysine									
Domestic CC methanol									
Domestic CC lysine									
Domestic CC sugar									
Domestic CC ethanol									
Objective function									

	Tons EC+CC molasses	EC suc in mill	CC suc in mill	Tons suc EC+CC	tons bagasse boiler A	Int Boiler A	tons bagasse boiler B	Int Boiler B E	ctricity total cane crushed
CC supplied									
EC supplied									
tons of CC bagg supplied									
tons of EC bagg supplied									
CC sucrose supplied			1						
EC sucrose supplied		1							
CC molasses supplied									
EC molasses supplied									
Cane Crushing tons EC+CC									
Bagg EC+CC tons									
CC+EC suc tons		-1	1	1					
CC+EC molassses tons	1								
Bagg to the boiler					1		1		
Boiler A					-1	284256			
Boiler B							-1	300000	
Boiler choice						1		1	
Electricity supply Boiler (MWh)					-0,24		-0,333		1
Electricity demand (tons) (MWh)									1
Excess bagg					-1		-1		
Excess bagg transfer									
BRFP1 capacity									
BRFP1 produced/ton r.m									
BRFP1 conversion factor									
clear juice tons in the mill				-1,25					
clear juice tons transfer									
BRFP2 capacity									
BRFP 2 produced/ton r.m									
BRFP2 conversion factor									
Syrup tr									
Syrup to A mol and A sugar									
Tons molasses produced									
Total tons molasses produced in mill	1								
BRFP3capacity									
BRFP3 produced/ton r.m									
BRFP3 conversion factor									
Tons sugar from syrup									
Total sugar produced									
Sugar conversion factor									
SS&DD sugar									
SS&DD ethanol									
SS&DD methanol									
SS&DD lysine									
Domestic CC methanol									
Domestic CC lysine									
Domestic CC sugar									
Domestic CC ethanol									
Objective function						0		-210	

	Surplus Electricity	Excess bagg	Storage	INT BRFP 1	Bagg to BR	BRFP 1 qu	BRFP1 mill	INT BRFP 2/ Bioethanol EC	CC Clear juice tons	CJ to BRFP2 pdtn/Bio-ethanol
CC supplied										
EC supplied										
tons of CC bagg supplied										
tons of EC bagg supplied										
CC sucrose supplied										
EC sucrose supplied										
CC molasses supplied										
EC molasses supplied										
Cane Crushing tons EC+CC										
Bagg EC+CC tons										
CC+EC suc tons										
CC+EC molassses tons										
Bagg to the boiler										
Boiler A										
Boiler B										
Boiler choice										
Electricity supply Boiler (MWh)										
Electricity demand (tons) (MWh)-	1					0				
Excess bagg		-1			-1					
Excess bagg transfer		-1	1		1					
BRFP1 capacity				255528	1					
BRFP1 produced/ton r.m					-0,312	1				
BRFP1 conversion factor						-1	1000000			
clear juice tons in the mill									1	
clear juice tons transfer									-1	1
BRFP2 capacity								102854		-1
BRFP 2 produced/ton r.m										-0,483
BRFP2 conversion factor										
Syrup tr										
Syrup to A mol and A sugar										
Tons molasses produced										
Total tons molasses produced in mill										
BRFP3capacity										
BRFP3 produced/ton r.m										
BRFP3 conversion factor										
Tons sugar from syrup										
Total sugar produced										
Sugar conversion factor										
SS&DD sugar										
SS&DD ethanol										
SS&DD methanol							-1			
SS&DD lysine										
Domestic CC methanol										
Domestic CC lysine										
Domestic CC sugar										
Domestic CC ethanol										
Objective function	0,00034425		0	124-0,00149				-173,2476448	0	0,005230275

	BFRP 2 quantity sold	BRFP2 produced	CJ toEvaporating pan	INT BRF3 invstmt	Tons syrup produced	Syr to BRFP3 pdtn/Lysine	BRFP3 quantity sold	BRFP3 in millions
CC supplied								
EC supplied								
tons of CC bagg supplied								
tons of EC bagg supplied								
CC sucrose supplied								
EC sucrose supplied								
CC molasses supplied								
EC molasses supplied								
Cane Crushing tons EC+CC								
Bagg EC+CC tons								
CC+EC suc tons								
CC+EC molassses tons								
Bagg to the boiler								
Boiler A								
Boiler B								
Boiler choice								
Electricity supply Boiler (MWh)								
Electricity demand (tons) (MWh)	0						0	
Excess bagg								
Excess bagg transfer								
BRFP1 capacity								
BRFP1 produced/ton r.m								
BRFP1 conversion factor								
clear juice tons in the mill								
clear juice tons transfer			1					
BRFP2 capacity								
BRFP 2 produced/ton r.m	1							
BRFP2 conversion factor	-1	1000000						
Syrup tr			-0,8		1			
Syrup to A mol and A sugar					-1	1		
Tons molasses produced								
Total tons molasses produced in mill								
BRFP3capacity				180503		-1		
BRFP3 produced/ton r.m						-0,376	1	
BRFP3 conversion factor							-1	1000000
Tons sugar from syrup								
Total sugar produced								
Sugar conversion factor								
SS&DD sugar								
SS&DD ethanol		-1						
SS&DD methanol								
SS&DD lysine								-1
Domestic CC methanol								
Domestic CC lysine								
Domestic CC sugar								
Domestic CC ethanol								
Objective function				-167,67		-0,00677069		

						DOMESTIC DEMAND SUGAR SEGMENTS							ETHANOL
	Syrup to A Sugar & Amol ton	s molasses ton	s sugar Tot	l Sugar quantiy Su	gar in millions	1	2	3		4	5	EXPORT SE	1
CC supplied													
EC supplied													
tons of CC bagg supplied													
tons of EC bagg supplied													
CC sucrose supplied													
EC sucrose supplied													
CC molasses supplied													
EC molasses supplied													
Cane Crushing tons EC+CC													
Bagg EC+CC tons													
CC+EC suc tons													
CC+EC molassses tons													
Bagg to the boiler													
Boiler A													
Boiler B													
Boiler choice													
Electricity supply Boiler (MWh)													
Electricity demand (tons) (MWh)													
Excess bagg													
Excess bagg transfer													
BRFP1 capacity													
BRFP1 produced/ton r.m													
BRFP1 conversion factor													
clear juice tons in the mill													
clear juice tons transfer													
BRFP2 capacity													
BRFP 2 produced/ton r.m													
BRFP2 conversion factor													
Syrup tr													
Syrup to A mol and A sugar	1												
Tons molasses produced	-0,3	1											
Total tons molasses produced in mill		-1											
BRFP3capacity													
BRFP3 produced/ton r.m													
BRFP3 conversion factor													
Tons sugar from syrup	-0,7		1										
Total sugar produced			-1	1									
Sugar conversion factor				-1	1000000								
SS&DD sugar					-1	0,15	0,21	0,23		0,25	0,27	1	
SS&DD ethanol													0,02
SS&DD methanol													
SS&DD lysine													
Domestic CC methanol													
Domestic CC lysine													
Domestic CC sugar						1	1	1		1	1		
Domestic CC ethanol													1
Objective function						0	0	0		0	0	0	105

	RTHANOL OMESTIC DEMAND SEGMENTS				METHANOL DD SEGMENTS					LYSINE DD SEGMENTS						
	2	3	4	5	1	2	3	4	5	1	2	3	4	5	RHS	
CC supplied															=	0
EC supplied															=	0
tons of CC bagg supplied															≤0	
tons of EC bagg supplied															≤0	
CC sucrose supplied															≤0	
EC sucrose supplied															≤0	
CC molasses supplied															=	0
EC molasses supplied															=	0
Cane Crushing tons EC+CC															=	0
Bagg EC+CC tons															=	0
CC+EC suc tons															=	0
CC+EC molassses tons															=	0
Bagg to the boiler															≤0	
Boiler A															≥0	
Boiler B															≥0	
Boiler choice															≤1	
Electricity supply Boiler (MWh)															≤0	
Electricity demand (tons) (MWh)															=	0
Excess bagg															≤0	
Excess bagg transfer															≤0	
BRFP1 capacity															≥0	
BRFP1 produced/ton r.m															=	0
BRFP1 conversion factor															≤0	
clear juice tons in the mill															≤0	
clear juice tons transfer															≤0	
BRFP2 capacity															≥0	
BRFP 2 produced/ton r.m															=	0
BRFP2 conversion factor															≤0	
Syrup tr															≤0	
Syrup to A mol and A sugar															≤0	
Tons molasses produced															≤0	
Total tons molasses produced in mill															≤0	
BRFP3capacity															≥0	
BRFP3 produced/ton r.m															=	0
BRFP3 conversion factor															≤0	
Tons sugar from syrup															=	0
Total sugar produced															=	0
Sugar conversion factor															≤0	
SS&DD sugar															≤0	
SS&DD ethanol	0,025	0,03	0,04	0,045											≤0	
SS&DD methanol					0,01	0,015	0,018	0,02	0,025						≤0	
SS&DD lysine										0,15	0,03	0,25	0,05	0,065	≤0	
Domestic CC methanol					1	1	1	1	1						≤1	
Domestic CC lysine										1	1	1	1	1	≤1	
Domestic CC sugar															≤1	
Domestic CC ethanol	1	1	1	1											≤1	
Objective function	107,825	101,25	60	25,3125	51,75	60,75	52,65	45	16,875	2250	497,13	668,52	714,25	817,115		Max!

APPENDIX O Definition of coefficient values and literature sources for data used in the BAM model

B_{14} *Boiler A* $-X_{21} + 284\ 256X_{22} \geq 0$	*284 256 tons bagasse is the maximum capacity of the inefficient boiler-bagasse flow rate per hour x the total number of operating hours of the mill:* *47tons/hr (Guest, 2019) x 6048*
B_{15} *Boiler B* $-X_{23} + 300\ 000X_{24} \geq 0$	*300 000 tons bagasse is the maximum capacity of the efficient boiler. Same calculation as above with a higher flow rate of 50tons/hr.*
B_{17} *Electricity supply Boiler (KWh)* $-240X_{21} - 333X_{23} + X_{25} \leq 0$	*1 ton of bagasse fed to Boiler A produces 240Kw of electricity and 1 ton of bagasse to Boiler B produces 333Kw of electricity* *IRENA, 2019*
B_{18} *Electricity demand (tons) (KWh)* $-32X_{11} + X_{25} - X_{26} = 0$	*Cane crushing demands 32Kw of energy* *IRENA, 2019*
B_{21} *BRFP1 capacity* $255\ 528X_{29} - X_{30} \geq 0$	*The maximum number of units that can be produced for BRFP1 is 255 528* *Gorgens et al., 2015*
B_{22} *BRFP1 produced/ton raw material (r.m)* $-0.312X_{30} + X_{31} = 0$	*For every ton of bagasse , 0.312 tons of BRFP1 is produced* *Gorgens et al., 2015*
B_{23} *BRFP1 conversion factor* $-X_{31} + 1\ 000\ 000X_{32} \leq 0$	*This equation converts the quantity of BRFP1 produced into millions*
B_{24} *Total clear juice tons in the mill* $-1.25X_{20} + X_{34} \leq 0$	*100 tons of cane producs 1.25 tons of mixed juice- Pillay, 2012*
B_{26} *BRFP2 capacity* $102\ 854X_{39} - X_{35} \geq 0$	*The maximum number of units that can be produced for BRFP2 is 102 854* *Naidoo et al., 2019a, b, Step Bio briefing notes*
B_{27} *BRFP 2 produced/ton r.m* $-0.483X_{35} + X_{36} = 0$	*For every ton of clear juice, 0.483 tons of BRFP2 is produced* *Naidoo et al., 2019a, b, Step Bio briefing notes*
B_{28} *BRFP2 conversion factor* $-X_{36} + 1\ 000\ 000X_{37} \leq 0$	*This equation converts the quantity of BRFP2 produced into millions*
B_{29} *Syrup transfer* $-0.8X_{38} + X_{40} \leq 0$	*0.8 tons of syrup remain for every ton of clear juice sent to the evaporating pan*
B_{31} *Tons molasses produced in mill* $-0.3X_{44} + X_{45} \leq 0$	*0.3 tons of molasses are produced for every ton of syrup*

B_{33} *BRFP3capacity* $180\ 503X_{39} - X_{41} \geq 0$	*The maximum number of units that can be produced for BRFP3 is 180 503* *Naidoo et al., 2019a, b, Step Bio briefing notes*
B_{34} *BRFP3 produced/ton r.m* $0.376X_{41} + X_{42} = 0$	*For every ton of syrup, 0.376 tons of BRFP2 is produced* *Naidoo et al., 2019a, b, Step Bio briefing notes*
B_{35} *BRFP3 conversion factor* $-X_{42} + \ 1\ 000\ 000X_{43} \leq 0$	*This equation converts the quantity of BRFP3 produced into millions*
B_{38} *Sugar conversion factor* $X_{47} + 1\ 000\ 000X_{48} \leq 0$	*This equation converts the quantity of sugar produced into millions*