EVALUATION OF SYSTEMS TO HARVEST, PROCESS AND TRANSPORT SUGARCANE BIOMASS

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ABSTRACT

One of the problems facing the world today is the fact that fossil fuel reserves are declining and, as a result, petrol and diesel costs are increasing. For the past century, fossil fuels have been the primary fuel source for most countries around the world and this has had an impact on the environment. This has resulted in the South African government, in line with international trends, investigating alternative energy sources to supplement and meet an increasing demand for energy. Biomass (e.g. leaves of sugarcane, referred to as sugarcane residue) is receiving increasing attention, as it is a sustainable and environmentally-friendly source of renewable energy. In South Africa, the majority of the sugar industry manually harvests burnt sugarcane. Thus, innovative residue recovery systems need to be developed to accommodate the manual harvesting of green/unburnt sugarcane. In this document, sugarcane residue refers to green/wet and brown/dry leaves, tops and green leaves constitute green residue, brown leaves constitute dry residue, and bagasse is the pulp left after the juice has been extracted from the sugarcane stalks. The name ‘residue recovery route’ encompasses both green and dry residue as, although ideally dry residue is collected, some residue recovery routes collect green residue in addition to dry residue.

The objectives of this study are: (i) to assess the potential energy available from dry sugarcane residue, taking into account the benefits of leaving a residue blanket in the field, and (ii) to investigate the harvesting systems, energy and costs required to recover the residue and deliver it to a mill for both new production and harvesting systems and systems currently used in South Africa, which range from manual harvesting to fully mechanised systems.

Current residue recovery methods, as well as potential methods which are still under development, are reviewed in this document. A costing model has been adopted and further developed, with the objective of estimating the costs incurred by residue collection and transport. The different residue recovery routes, which were identified in the literature review, were incorporated into the model. These routes include different methods of harvesting, residue separation infield or at the mill, the method of residue collection, residue processing and the transportation of the residue. Processing to increase the bulk density of the sugarcane residue prior to transport has been considered in this study, as its low bulk density has been identified as a critical issue in other studies. By processing the residue, the energy density and bulk density of the residue can be increased, which, in turn, improves the transport efficiency. Problems encountered when modelling residue processing included

estimating the capital cost requirements, as well as the maintenance and operating costs, for each processing plant. The model was applied to two case studies, in order to compare the costs for each individual residue recovery route. This enabled the lowest cost and appropriate residue recovery route to be identified for the case studies. The cost per unit energy was used to compare the cost of the residue recovery to the cost of coal at the mill, which is required to determine whether sugarcane residue is an economically-viable source of renewable energy. Based on the assumptions made for the lowest cost routes which were identified, it was found that the cost of the residue recovery i.e. the cost of the residue, was less than that of coal and, thus, these routes are potentially economically beneficial for the mill.

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

The South African government, in line with international trends, has investigated alternative energy sources to help supplement and meet the increasing national demand for energy. The government has set a target of 3 725 megawatts (MW) of power that needs to be generated from renewable energy sources to ensure the continued uninterrupted supply of electricity. This 3 725 MW is broadly in accordance with the capacity allocated to renewable energy generation in the Integrated Resource Plan for Electricity (IRP) 2010-2030 (Energy, 2013). The use of biomass (e.g. sugarcane residue) as a feedstock for energy production is receiving widespread attention, as it is a sustainable and environmentally-friendly source of renewable energy. Biomass from sugarcane is unequalled by any other plant when managed for energy production (Gosnell *et al.*, 2011). This interest in biomass has resulted in the use of the term 'cogeneration', which is the process by which both thermal energy (steam) and electrical power are produced (Hofsetz and Silva, 2012). Cogeneration is especially relevant to the sugarcane industry, as sugarcane residue and bagasse can be used in sugar mills for steam generation, which is primarily used to generate electricity (Mbohwa and Fukuda, 2003).

The harvesting operation of sugarcane is currently the one aspect of sugarcane production which continues to be the least technically advanced. In South Africa, up to 90% of the sugarcane is burned before harvesting to allow for easier manual harvesting (Meyer, 2005). However, the harvesting of green sugarcane is being promoted as a consequence of environmental pressure, legislation and the availability of improved harvesting systems. In the past, sugarcane residue was not seen as an energy source and thus not a potential source of income. However, with the development of green sugarcane harvesting, this view is changing (Braunbeck *et al.*, 1999). The sugar industry is unique because it supplies a localised and rich source of biomass fibre, which can be utilised to produce electricity and biofuel (Meyer *et al.*, 2012). This biomass fibre, which consists of bagasse and sugarcane residue, can be considered as a source of renewable energy which has the potential to replace or supplement energy from fossil fuels, and it also has significant potential in the generation of electricity.

Energy recovery from sugarcane residue could provide a useful source of revenue. The challenge is how to recover the sugarcane biomass to produce energy in an efficient and cost-competitive way. This is essential if green sugarcane harvesting is to become financially viable and if it is to be widely adopted. In addition, the adoption of green sugarcane harvesting will contribute to both the economic and environmental sustainability of the sugarcane industry (Braunbeck *et al.*, 1999). Although sugarcane residue can be used as a source of energy, removing all the residue from a field after harvesting is not recommended, as it is desirable in most production climates to leave a residue blanket for agronomic reasons (Braunbeck *et al.*, 1999).

In Brazil, approximately 70% of the sugarcane is harvested green (no burning), with the mills not only being able to produce enough electricity to fulfill their power requirements, but also being able to produce surplus electricity, which can then be sold to the national grid (Fortes *et al.*, 2012). In comprehensive studies conducted in Australia into methods of improving sugarcane residue bulk density, it was found that further development is required, before current residue recovery methods can be considered economically feasible (Corporation, 2011). The reason why residue recovery is economically viable for growers in Brazil, is because the government provides growers with financial incentive by the establishment of the Brazilian Program of Incentives for Alternative Sources of Electrical Power (Hofsetz and Silva, 2012). Other countries which have implemented the use of sugarcane residue as an alternate fuel to fossil fuels at the mill, to help generate power year round, include Mauritius, Reunion, Guadolupe and Guatemala (Hassuani *et al.*, 2005).

There have been studies conducted in South Africa which have investigated the use of sugarcane residue as an energy source. A few factors separate the South African sugar industry from other sugarcane-growing countries. Sugarcane in South Africa is predominantly manually harvested, which makes the option of residue collection in conjunction with a chopper harvester unlikely (Meyer, 2005). The average sugarcane yields in South Africa are less than in other sugarcane growing countries, which will influence the amount of residue available and thus the economics of collecting the residue (Langton, 2013). If the South African government were to provide subsidies to sugarcane growers who practise residue recovery, then residue recovery may be a viable option, but at present the government does not do so, which has resulted in few farmers attempting to recover residue in South Africa.

The objectives of this study are: (i) to assess the potential energy available from sugarcane residue, taking into account the benefits of leaving a residue blanket in the field, and (ii) to investigate the harvesting systems, energy and costs required to recover the residue and deliver it to a mill for the different production and harvesting systems used in South Africa, which range from manual harvesting to fully mechanised systems.

Chapter 2 contains a review of the potential recoverable energy from sugarcane and an overview of sugarcane residue recovery and the recovery systems available. This chapter provides some insight into which residue recovery routes could be included in this study. Chapter 0 contains a review of the model selected for use in this project. Chapter 4 contains details of the model development, while Chapters 5 and 0 include the model validation and the model application. Lastly, Chapter 7 includes a discussion, as well as the conclusions and recommendations emanating from the results of this project.

2. AN OVERVIEW OF SUGARCANE RESIDUE RECOVERY AND THE RECOVERY SYSTEMS AVAILABLE

A review of potential sugarcane residue recovery and processing techniques, which could be applicable in South Africa, and the economics of each of these, will be covered in this chapter.

2.1 Background to Sugar Production

There are approximately 29 130 sugarcane growers who are currently registered in South Africa. These growers produce an annual average of 19.9 million tons of sugarcane in 14 mill supply areas. These areas extend from the Mpumalanga Lowveld down to Northern Pondoland in the Eastern Cape (SASA, 2012).

Of the registered growers in South Africa in 2012, 27 580 were small-scale growers who produced 8.1% of the total sugarcane crop, and approximately 1 550 were large-scale growers who produced 84.7% of total sugarcane crop. The remaining 7.2% was produced by milling companies that own sugar estates. Of the 1 550 large-scale growers, there were 378 emerging black farmers (SASA, 2012). Since the start of the 1990's, there has been a declining trend in the sugarcane labour force, but in recent years this trend has stabilised at approximately 70 000 workers (Growers, 2011).

Sugarcane has been grown in South Africa since 1847 and manual harvesting has always dominated the industry. Depending on the climatic and soil conditions of the area, the average sugarcane crop cycle varies between 12 and 24 months. The sugarcane grown in coastal areas is generally harvested every 12 months, whilst inland areas have a crop cycle of approximately 24 months (Langton, 2013). In a survey conducted in 2003, it was shown that 97% of sugarcane in South Africa was manually cut and that over 90% was burnt before harvesting (Meyer, 2005). The harvesting season in South Africa is between April and December. In a report by the South African Sugar Association (2012), which reviewed the South African sugar production between the years 1997 to 2011, it is evident that, there is a decreasing trend in the total sugarcane crushed per season over this period. According to Singels *et al.* (2012), the average sugarcane yield in South Africa can vary between 40 and 100 t/ha, and has a relatively low average yield per hectare when compared to the yields in other countries like Brazil, which have an average yield of 140 t/ha, and Tanzania, which has an average of 110 t/ha (Paes and de Oliveira, 2005; Watson, 2011). However, these countries are either fully irrigated or receive a high amount of rainfall, unlike the South African sugar industry.

Currently, the pre-harvest burning of sugarcane is a very common practice because it simplifies the harvesting process by removing most of the sugarcane residue (Meyer *et al.*, 2005a). It has been found that up to 90% of the brown leaves are removed when burning occurs (Beeharry, 1996). Burning can have negative effects, for example, the loss of available nutrients from the soil and the regrowth of the sugarcane can be affected when the sugarcane stubble is damaged by the heat of the burning residue. Earthworms and beneficial soil microorganisms are also affected negatively, when burning occurs (Prabhakar *et al.*, 2010).

Increasing attention is being given to the utilisation of sugarcane residue as a source of energy (Wienese and Purchase, 2004). Sugarcane residue can contain between 28% and 50% of the total energy stored in sugarcane (Deepchand, 1989; Beeharry, 2001; Prabhakar *et al.*, 2010). This justifies the need for systematic research, to identify the most efficient method of utilising this renewable source of energy. Appropriate residue collection mechanisms, as well as attractive markets, will help make the sugarcane industry more self-sustainable and more profitable.

The percentage of the total sugarcane plant biomass that is constituted by the residue (wet mass), varies considerably and depends on the sugarcane variety, the age of the sugarcane, the climate and the soil. In South Africa, the total residue percentage of the sugarcane plant varies between 20% and 35%, in Columbia between 10% to 40%, in Cuba approximately 30.5% and 14% in Brazil (Leal, 2007; Donaldson *et al.*, 2008; Romero *et al.*, 2009; Oliveira and Maltempi Ferreira, 2010). Other studies have found that residue levels average at approximately 40% (Prabhakar *et al.*, 2010) and 20% (Beeharry, 1996). A number of factors govern how much residue can potentially be recovered from the field. These factors include: sugarcane variety, climate, stage of cut, location of the field, degree of lodging and harvesting period. In some cases, it has been found that it is advisable to completely remove the residue from the field (Marchi *et al.*, 2005).

Green sugarcane harvesting is a pre-requisite for residue recovery, but has been seen in a negative light because it occurs at a slower rate than harvesting burnt sugarcane (Rein, 2005; Müller and Coetsee, 2008). However, this view has changed, as residue is now seen as a possible renewable source of energy, therefore green sugarcane harvesting and residue recovery may be economically feasible. Green sugarcane harvesting is discussed in the following section.

2.2 Green Sugarcane Harvesting

Sugarcane harvesting and processing is currently going through many technological advances (Oliveira and Maltempi Ferreira, 2010). The implementation of these new systems has a direct influence on the soil's physical and biological properties. When sugarcane is burnt, most of the nutrients, which were removed from the soil during the growth stage, are lost and will not be returned to the soil (Fortes *et al.*, 2012). As a result, the soil structure in many sugarcane fields has been compromised.

In Brazil, the burning of sugarcane before harvesting is not currently practised because of environmental concerns and legislation (Fortes *et al.*, 2012). When sugarcane is burnt, carbon monoxide (CO) and particulate matter are released, which can have an adverse effect on human health and can cause damage to the environment. The most prevalent human illnesses are respiratory-related, which can be aggravated by inhaling the sugarcane smoke (Braunbeck *et al.*, 1999). Not only does the burning of sugarcane have a negative environmental effect, but it also results in a lower sugar yield because of the increased deterioration rate of the sugarcane during the harvest to crush delay (Braunbeck *et al.*, 1999).

The presence of residue in the field will result in agronomic benefits such as improved moisture retention, reduced weed growth and enhanced soil nutrient balance (Braunbeck *et al.*, 1999; Fortes *et al.*, 2012). The residue will provide soil surface protection from rain and wind, which reduces erosion and soil temperature variations, and increases water infiltration and biological activity (Marchi *et al.*, 2005). The residue which is left on the soil surface also has the potential to increase the carbon (C) concentrations, thus improving the structure of the soil (Blair, 2000; Fortes *et al.*, 2012).

Although there are significant advantages to having a residue blanket in sugarcane fields, there are also some potential drawbacks, such as lower manual harvesting performance, lower chopper harvester pour rates, lower mechanical loading rates and lower vehicle payloads (Meyer *et al.*, 2005b). In addition, the residue blanket poses a fire hazard, it may start rotting in wet areas, mechanical cultivation becomes difficult, the ratooning of the sugarcane can be delayed and the pest population could increase because of the environment created under the residue blanket (Marchi *et al.*, 2005). It is therefore important to conduct technical and economic viability analyses before any residue is removed. These analyses should take into account the loss of the residue-herbicide effect, among other considerations. It has been found that if less than 7.5 t/ha of residue is left infield, then the field will require the use of chemical and physical weed control. It is therefore important to keep the residue level above 7.5 t/ha (Marchi *et al.*, 2005).

Marchi *et al.* (2005) set out a number of guidelines to indicate: (i) when residue should be removed, (ii) when it can be removed after analysis, and (iii) when it can be partially removed. They stipulate that residue should only be removed when the sugarcane fields are near inhabited areas, in areas where there is a high lightning risk that may cause fire, in areas which are very humid and cold, or before replanting in fields infested with soil pests

The guidelines stipulate that the residue can be removed, but only after a local analysis has been conducted. This includes assessing if the variety of sugarcane has delayed ratooning in the presence of the residue, if the harvested areas have a high incidence of sugarcane pests, or if the equipment has difficulty planting through the residue blanket. In fields where a large residue blanket reduces the crop yield, the residue should only be partially removed, maintaining the minimum required residue blanket (Marchi *et al.*, 2005).

Many studies have shown that green sugarcane harvesting is a more environmentally-friendly harvesting technique, compared to burnt sugarcane harvesting (Braunbeck *et al.*, 1999; Blair, 2000; Marchi *et al.*, 2005), and if the practice is conducted in the correct manner, it can be more profitable than the pre-harvest burning of sugarcane, especially if the sugarcane residue is used to generate income. A study by Norris (2008) found that sugarcane residue can increase gross returns per hectare by 10-15%. The energy that is available in a sugarcane plant is discussed in Section 2.3, whilst residue recovery routes are discussed in Section 2.4.

2.3 Energy Contained in Sugarcane

In order to establish the efficacy of sugarcane as a source of energy, a comparison can be made to oil. One ton of oil contains approximately 42 GJ of energy, whilst one ton of fresh sugarcane biomass (stalk and leaves) contains approximately 7400 MJ, which translates to 17.6% of the energy contained in oil (Leal, 2007). Assuming that one barrel of oil (0.159 m^3) contains 6170 MJ, the energy value of one ton of sugarcane is equivalent to 1.2 barrels of crude oil, and a yield of 70 t/ha is equivalent to 84 barrels of crude oil per hectare (Oliveira and Maltempi Ferreira, 2010). A further comparison with coal suggests that the recoverable residue per hectare is equivalent to ten tons of coal (de Carvalho Macedo *et al.*, 2001; Leal, 2007; Smithers, 2014). For a clean sugarcane yield of between 75 – 80 t/ha, a residue yield of between 12 – 17 tons can be expected. This yield is equal to a primary energy value of approximately 50 000 kWh per hectare (Prabhakar *et al.*, 2010).

2.3.1 Sugarcane plant energy breakdown

The energy available for cogeneration could potentially double, if sugarcane residue is utilised as a fuel source (Wienese and Purchase, 2004). The energy contained in the sugarcane plant can be broken down into three components: the stalk fibres, leaf fibres (residue) and sugar. Each of these contains approximately one-third of the total energy in sugarcane (Leal, 2007; Oliveira and Maltempi Ferreira, 2010). The total energy contained in sugarcane is estimated at 7400 MJ/t. The sugarcane energy breakdown is summarised in Table 2.1.

Table 2.1 Primary energy from 1 ton of sugarcane (Leal, 2007; Alonso-Pippo *et al.*, 2008)

Component (dry basis)	Energy (MJ/t of clean sugarcane stalks)
142 - 150 kg of sugar	2257 - 2500
135 - 140 kg of stalk fibres	2184 - 2400
140 kg of leaf fibres	2184 - 2500
Total (422 - 430 kg)	6625 - 7400

2.3.2 Energy available in South Africa

A study was conducted by Smithers (2014) with the objective of estimating the amount of recoverable residue available in South Africa and therefore estimating the quantity of energy available in residue recovery in South Africa. A number of assumptions were used in this study, namely: (i) a dry residue yield of 12.3% of the sugarcane stalk, (ii) a residue recovery efficiency of 50%, (iii) a residue energy value of 2300 MJ/t, (iv) period of operation for the mill is 200 days, and (iv) there is no energy loss in the generation process. The results from this study are found in Table 2.2.

Table 2.2 Sugarcane residue power generation potential in South Africa (Smithers, 2014)

	Value
Sugarcane stalk yield (t)	22 000 000.0
Area (ha)	430 000.0
Sugarcane stalk yield (t/ha)	51.2
Potential residue from sugarcane (%)	12.3
Potential residue from sugarcane (t/ha)	6.3
Recovery residue from field (%)	50.0
Utilisable residue (t/ha)	3.1
Residue left in field (t/ha)	3.1
Required residue blanket (t/ha)	3.0
Available residue at mill (t)	1 353 000.0
Energy from residue (MJ/t)	2 300.0
Total energy delivered to mill (GJ)	3 111 900.0
Length of milling season (days)	200.0
Total Power available (MW)	180.1

For an annual sugarcane stalk yield of 22 000 000 tons, there are expected to be 1 353 000 tons of residue available for energy use at the mill. This translates to 3 111 900 GJ of energy available and there is therefore the potential to generate at a rate of 180.1 MW for 200 days per annum from sugarcane residue in South Africa (Smithers, 2014).

2.4 Residue Recovery Systems

As with other forms of biomass, the sugarcane residue has a relatively low bulk density, which results in both high recovery and transport costs (Hassuani *et al.*, 2005). Therefore, residue recovery systems need to focus on increasing the residue bulk density, in order to improve the recovery and transport efficiencies. Figure 2.1 depicts the linear relationship between transport costs and bulk density. The savings represented in Figure 2.1 are savings alone and do not include any costs (Corporation, 2011).

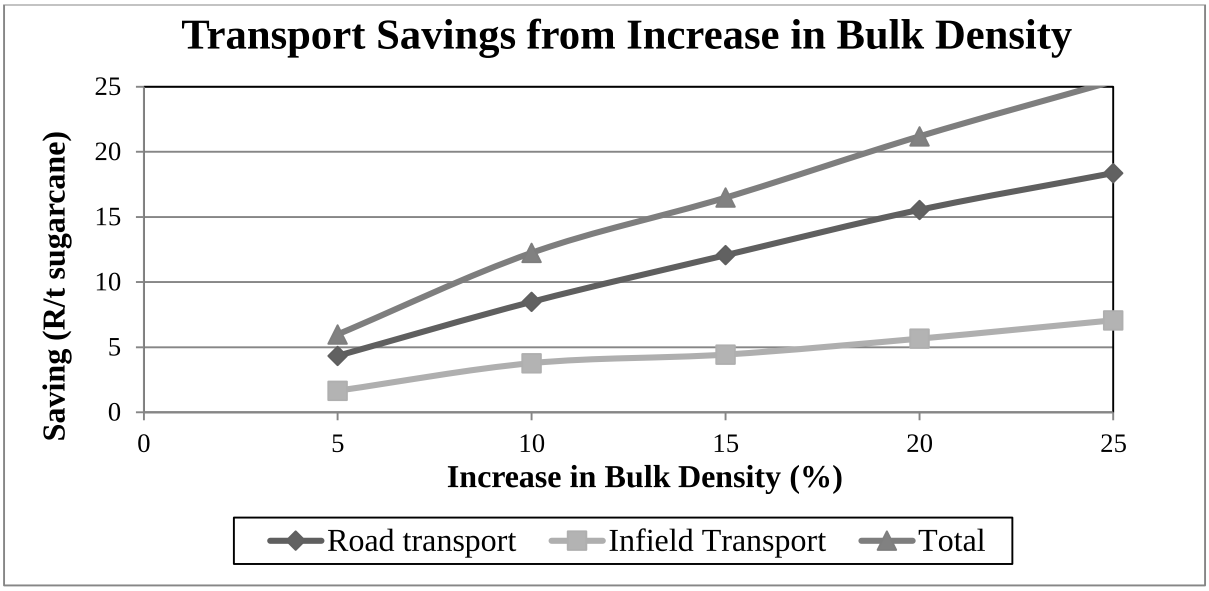

Figure 2.1 Transport savings (R/t of sugarcane) from increase in bulk density (after SRDC, 2011) converted using an exchange rate of AUD $ 1 = R 9.42

A number of residue recovery methods are currently being implemented. These include baling, forage harvesting and collecting residue, using a chopper harvester with the separation fans turned off (Hassuani *et al.*, 2005). Under the post-harvest infield residue collection scenario, there are a number of factors which govern how economical the recovery process will be. These include the harvesting and loading techniques which are used to recover the residue, as well as the topography and rockiness of the field (Beeharry, 2001). The amount of residue which will be collected will be defined by the sugarcane harvesting cleaning efficiency and the residue recovery efficiency (Hassuani *et al.*, 2005). There are two fully mechanised sugarcane harvesting technologies available today, namely, the whole-stick harvester system and the chopped sugarcane system, also known as a chopper harvester (Braunbeck *et al.*, 1999).

Much research has been conducted on residue recovery systems and these systems can be grouped into five main routes for harvesting sugarcane and for removing and collecting residue (Marchi *et al.*, 2005). Figure 2.2 displays these routes, labelled Route A, Route B, Route C, Route D and Route E.

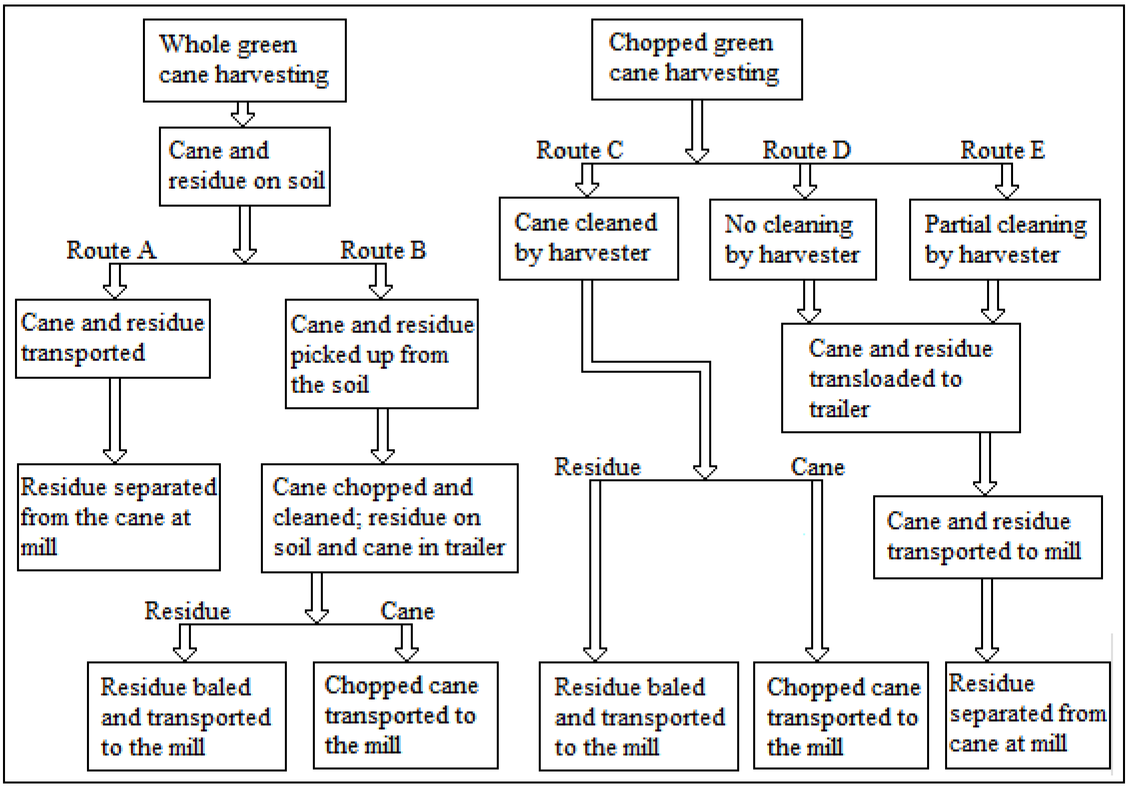

Figure 2.2 Selected routes for sugarcane harvesting with residue recovery (de Carvalho Macedo *et al.*, 2001)

2.4.1 Whole-stick harvesting

Whole-stick harvesting can be done manually or mechanically, although mechanical whole-stick harvesters currently are not widely used because of current sugarcane varieties, where lodging is prevalent, which causes whole-stick harvesters to struggle to operate (Lyne, 2014). For this reason, mechanical whole-stick harvesting has not been considered for this project. Manual whole-stick harvesting has been the prominent method of harvesting sugarcane since sugarcane cultivation began. Studies have found that the manual harvesting capacity is between 4 and 7 t/man/day (Marchi *et al.*, 2005). Routes A and B are two routes that can be used to remove the residue from the sugarcane, when whole-stick green sugarcane harvesting is practised.

2.4.1.1 Route A - sugarcane and residue separated at mill

In Route A, the sugarcane is cut manually and is placed on the ground in windrows, stacks or bundles, after which a loader loads the sugarcane into infield transport. The sugarcane is then either transported to the mill, or to a transloading site, where it is transloaded to road transport. The sugarcane tops are left infield during harvesting. The dry residue is separated from the sugarcane at a dry cleaning station at the mill (Marchi *et al.*, 2005).

There are three major advantages to using this route, namely: (i) there are no trucks in the fields, which reduces damage to stools and the soil structure, (ii) the harvesting and loading operations are independent of each other and therefore harvesting can continue when there is a shortage of trucks, and (iii) truck operations can be optimised, as no time is spent in the field (Marchi *et al.*, 2005).

2.4.1.2 Route B - sugarcane and residue separated infield

Route B consists of the sugarcane being cut manually. The residue is manually separated from the sugarcane, with the sugarcane being placed in windrows, stacks or bundles, and the residue being placed in a separate windrow. The sugarcane is loaded by the loader onto infield transport, after which the sugarcane is either transported to the mill, or to a transloading site, where it is transloaded to road transport. The green residue and dry residue are left infield. It is not possible to separate green and dry residue on the ground and thus the residue as a whole is collected using a residue recovery machine.

Another option for Route B is to mechanically clean the sugarcane infield, but not to chop the sugarcane into billets. Trials are being conducted just outside Port Shepstone, South Africa, on equipment which cleans the sugarcane infield (Langton, 2013). At present the equipment can only clean 2 t/h, which is not economically feasible and is far short of the break-even processing rate of 5 t/h. Hence, it is currently not feasible to mechanically clean ‘whole-stick’ sugarcane infield (Langton, 2013).

2.4.2 Chopper harvester

A chopper harvester cuts the sugarcane, which is then chopped into billets inside the harvester. Fans within the harvester separate the residue from the sugarcane billets. The billets are offloaded infield into trucks, which travel alongside the harvester. When chopper harvesters harvest unburnt (green) sugarcane, they are between 30 and 40% less productive than when harvesting burnt sugarcane (Braunbeck *et al.*, 1999).

The harvesting capacity of chopper harvesters can range between 400 and 600 t/machine/day in a 24h/day operation (Braunbeck *et al.*, 1999), but for South African conditions, this value is approximately 150 t/machine/day because of shorter working hours and transport inefficiency (Lyne, 2014). Akachi (2007) found that residue separation improved and harvesting losses decreased, with the increasing engine power of harvesters. Smaller harvesters were, however, less affected by wet infield conditions, when compared to larger harvesters, as they do not get stuck as easily.

Table 2.3 contains an initial comparison between Route C (conventional harvesting) and Route D (no residue removal during harvesting). There are positive aspects for both routes. Route C has a very low level of vegetal impurities and a high average payload; however, this results in a higher sugarcane loss because of the cleaning. Route D is characterised by a high level of vegetal impurities and lower average payload, which results in a lower sugarcane loss.

Table 2.3 Test results comparing Route C and Route D (Hassuani *et al.*, 2005)

Parameters	Route C	Route D
Harvesting vegetal impurities cleaning efficiency (%)	81.00	24.00
Soil in harvested load (%)	0.85	2.00
Vegetal impurities (dry matter) in the load (%)	2.30	12.00
Sugarcane losses related to clean harvested stalks (%)	6.30	1.00
Average truck trailer load (t)	20.60	10.60

2.4.2.1 Route C - sugarcane and residue separated infield

Route C consists of the sugarcane being cut and chopped into billets by the harvester. Separation fans clean the sugarcane infield. The chopped sugarcane is offloaded infield into a vehicle which drives alongside the harvester. The residue (green and dry) is left infield, to be recovered and transported separately to the mill (Marchi *et al.*, 2005)

A problem encountered with the cleaning system is that if the separation fans are run at a high speed, there is adequate cleaning, but there is increased sugarcane loss. If the fans are run at a lower speed, there will not be sufficient cleaning, but there will be a lower loss of sugarcane (Corporation, 2011).

The sugarcane residue mass balance for a conventional chopper harvester cleaning system can be seen in Figure 2.3. For this mass balance, 124.8 kg/ha of residue is taken to the mill, which amounts to 89% of the available residue in the field. A comparison of Routes C, D and E can be found in Section 2.6.1.

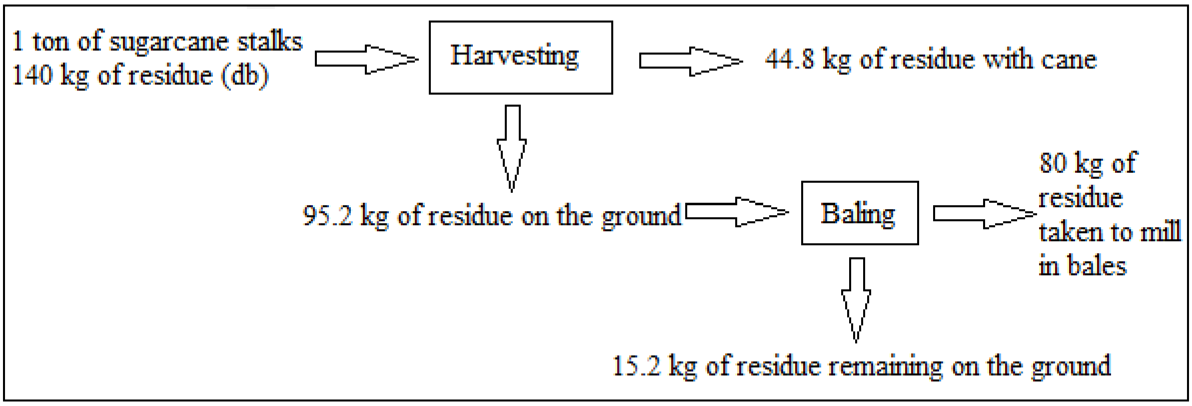

Figure 2.3 Sugarcane residue mass balance for Route C (de Carvalho Macedo *et al.*, 2001)

2.4.2.2 Route D - sugarcane and residue separated at mill

Route D consists of the sugarcane being cut and chopped into billets by the harvester. The dry residue is not separated from the sugarcane, as both the primary and secondary separation fans are switched off. The sugarcane billets, with the dry residue, are then transported to the mill. The dry residue will then be separated from the sugarcane at a dry cleaning station at the mill (Hassuani *et al.*, 2005; Marchi *et al.*, 2005; Norris, 2008). Some improvements and further optimisation can still be achieved through this route and the results could be promising (de Carvalho Macedo *et al.*, 2001). For this route, the sugarcane tops i.e. green residue, are left in the field, thus ensuring some protection of the soil. This route has the added advantage of making it easier to remove the dry leaves from the sugarcane stalk, as the sugarcane tops are left infield (Hassuani *et al.*, 2005).

By transporting the sugarcane and dry residue together, the bulk density of the combined load is lower and this results in a lower payload. The fact that there is no residue removal also means that the harvester has to operate at a lower ground speed; however, as there is more material being processed per hectare, there is not much difference in the operational capacity of the harvester (Hassuani *et al.*, 2005). Research found that by not using the separation fans, the sugarcane losses for an 84 t/ha field can be reduced by 4.5 t/ha (Hassuani *et al.*, 2005); however, the harvest operation will require more harvesters, otherwise it will take longer.

As there is no residue collection infield, this translates to less equipment being required. There will be less traffic infield, which, in turn, means there is less potential for soil compaction (Marchi *et al.*, 2005). It was also noted that the chopper harvesters and transport vehicles were not designed for this type of operation and therefore this equipment could be further optimised, if this option were to be seen as feasible (Hassuani *et al.*, 2005).

Figure 2.4 shows the residue recovery efficiencies throughout Route D. Seventy-six percent of the available residue in the field reaches the mill via this route. A comparison of Routes C, D and E can be found in Section 2.6.1.

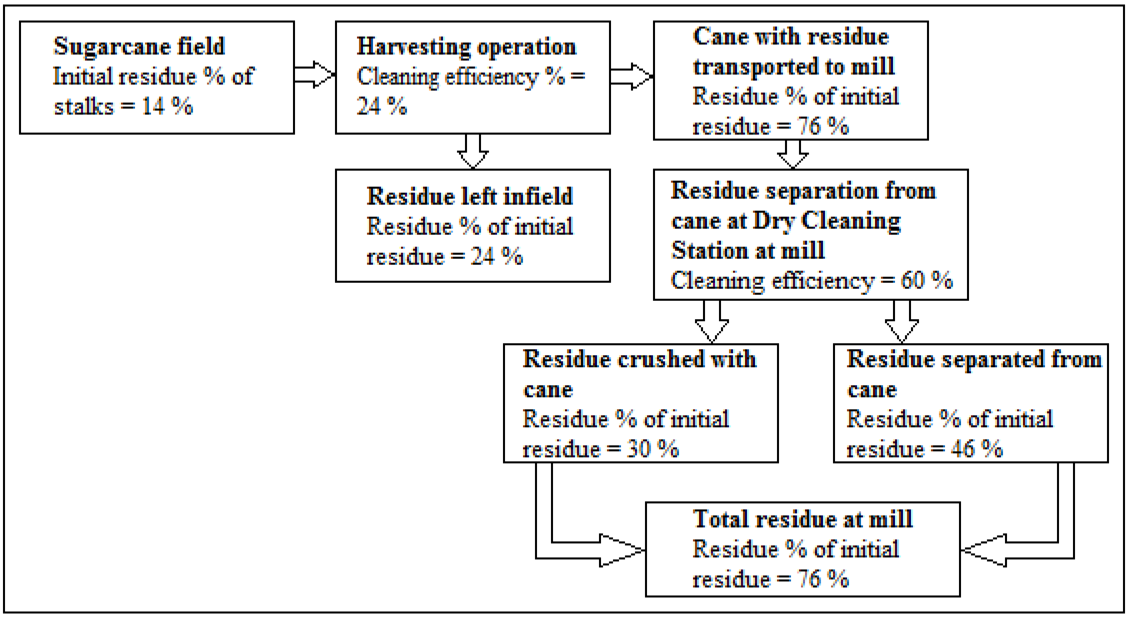

Figure 2.4 Route D recovery efficiencies (Hassuani *et al.*, 2005)

A variation of this system is to replace the separation fans in the harvester with shredder fans. This fan separates the residue from the sugarcane, but also shreds it. The bulk density of the residue can be increased by between 12 and 22%. The shredded residue is fed back onto the elevator and dumped into a truck with the sugarcane billets. Thus, the sugarcane and residue are transported together (Corporation, 2011) An additional benefit of shredded residue is that it has better flow characteristics. This reduction in residue particle size helps when feeding the residue into the furnace at the mill.

2.4.2.3 Route E – partial cleaning of sugarcane

Route E is a variation of Route D. For this route, the sugarcane is cut and fed into the harvester, where it is chopped into billets. The fans are run at a reduced speed, which results in the partial cleaning of the sugarcane, with approximately 50% of the residue left infield and the rest being transported with the sugarcane to the mill. The reason for this partial cleaning is to retain a residue blanket. The residue that is transported with the sugarcane to the mill has to be separated at a dry cleaning station (Marchi *et al.*, 2005). A comparison of Routes C, D and E is contained in Table 2.4.

Table 2.4 Test results for Routes C, D and E (Marchi *et al.*, 2005)

Parameter	Route C	Route D	Route E
Potential capacity - harvester (t/h)	63.0	57.0	63.0
Sugarcane field yield (t/ha)	139.0	156.0	148.0
Vegetal impurity			
Wet basis (%)	4.8	20.0	16.0
Dry basis (%)	2.3	15.0	11.0
Moisture content (%)	52.0	27.0	31.0
Mineral impurity (%)	0.1	0.38	0.22
Percentage of clean sugarcane (%)	95.1	79.6	83.8
Visible losses (t/ha)	3.7	1.7	2.0
Visible losses % clean sugarcane	2.7	1.4	1.6
Clean sugarcane yield estimate (t/ha)	136.0	126.0	126.0
Average load per infield transport unit (t)	6.0	2.8	3.6
Truck load density (kg/m^3)	410.0	240.0	270.0
Residue left on the soil			
Wet basis (t/ha)	17.0	1.5	7.7
Dry basis (t/ha)	16.0	1.4	7.0
Moisture content (%)	7.6	7.0	8.3
Harvester cleaning efficiency (%)	83.4	5.7	30.1

From Table 2.4, it can be seen that Routes D and E have a higher biomass yield, but a lower clean sugarcane yield, than Route C. Route C also has less vegetal impurities in the yield and the bulk density is considerably higher for Route C.

2.4.3 Infield residue recovery

Two methods of sugarcane residue recovery, namely, the use of a baler or a forage harvester, are currently being implemented. The use of a silage wagon has also been investigated. When infield residue recovery is implemented, there is little chance of separating the green and dry residue before collection, thus that which is collected is not completely dry.

2.4.3.1 Baling (Routes B and C)

The baling of sugarcane residue increases the residue density and also transforms it into standardised sizes (unit forms). It has the potential to reduce the cost of the loading and transportation operations and this is why it is an attractive residue recovery method (Hassuani *et al.*, 2005; Marchi *et al.*, 2005). A baler has a recovery efficiency of approximately 67% (Hassuani *et al.*, 2005). Baling is a popular option, as it has a high operating performance (t/h) (Marchi *et al.*, 2005). A factor to be considered is that the residue moisture content needs to be below 30% before baling. If it is higher than this value, there is a risk of spontaneous combustion (de Beer *et al.*, 1996).

Research has found that rectangular bales are better suited for sugarcane residue, because square balers can deal with sugarcane stalks in the residue better than round balers (Marchi *et al.*, 2005). Furthermore, from Table 2.5 it can be seen that rectangular bales have a high bulk density, but are light and easy to stack, when compared to round bales (Hassuani *et al.*, 2005). The problem with small rectangular bales, however, is that there are a large number of bales to recover from the field. Hence, research suggests that large rectangular bales are therefore best-suited for sugarcane residue recovery (Hassuani *et al.*, 2005; Marchi *et al.*, 2005). However, there are some disadvantages to large rectangular bales, namely, the high capital cost of large rectangular balers, the weight of the bales and the fact that they need to be stored under cover as they have relatively poor weather resistance (Marchi *et al.*, 2005).

This has led to many mills, which previously employed sugarcane residue baling, to now use round fixed drum balers. The reasons being, namely, the relatively low capital cost and maintenance requirements of round balers. In addition to this, round bales have a better weather resistance compared to rectangular bales (de Beer *et al.*, 1996; de Lange, 2014).

The way in which the sugarcane residue is raked before baling has a significant effect on the residue recovery efficiency. Raking can improve baler performance, reduce damage to the baler pickup system and also reduce baler maintenance costs. For an investigation into the effect of raking, a square baler was used and the results can be found in Table 2.6. It was suggested that it is best to rake two windrows into one large windrow before baling, as the bale will have a higher bulk density and the diesel consumption (l/t) for this raking option is also the lowest (Hassuani *et al.*, 2005).

Table 2.5 Comparison between small round bales, large round bales and small rectangular bales (Hassuani *et al.*, 2005)

Type of Bale	Small Round	Large Round	Small Rectangular
Baling system	Fixed drums	Belts	Press
Baler operational capacity (t/ha)	1.8	2.7	9.0
Bale weight (kg)	106.0	285.0	15.0
Bale bulk density (kg/m³)	118.0	95.0	112.0
Soil in the bale (%)	5.6	6.2	-
Residue recovery efficiency (%)	67.0	58.0	-

Table 2.6 Effect of raking on square bale specifications (Marchi *et al.*, 2005)

Bale parameters	Raking 1 × 1	Raking 2 × 1	No Raking
Size (m)	0.8 × 0.87 × 1.9		
Average weight (kg)	242.0	306.0	295.0
Bulk density (kg/m³)	183.0	231.0	223.0
Average moisture content (%)	12.0	15.3	13.1
Soil (%)	3.5	4.7	3.3
Baling operational parameters of dry clean residue			
Bales t/hour (baling + manoeuvres)	6.5	9.1	9.8
Diesel consumption (l/t residue)	2.0	1.5	1.6
Recovery efficiency (%)	56.0	84.0	73.0

Although there are many positive aspects to baling sugarcane residue, a number of drawbacks have been identified. These include a limited time frame for the baling operation, since tillage practices and sugarcane growth occur soon after harvest, the inability of the baler to handle soil irregularities, choking problems associated with the residue pickup mechanism because of the presence of sugarcane in the residue, the resultant high maintenance costs for the balers, damage to sugarcane stools and soil compaction, as a result of the infield movement of the baler. Furthermore, the residue needs to dry for longer periods if rain occurs, and soil is added to the residue during raking (Hassuani *et al.*, 2005).

2.4.3.2 Forage harvester (Routes B and C)

Forage harvesting takes place after the raking operation. A forage harvester collects and shreds the residue (brown and green leaves) and then transfers the shredded residue to a transport vehicle, which travels alongside the harvester (Hassuani *et al.*, 2005). Forage harvesters pick up more soil than balers and the density of the collected residue is only 66% of that of bales (de Beer *et al.*, 1996).

A forage harvester has a recovery efficiency of approximately 70% (Hassuani *et al.*, 2005). Some factors which affect the cost of forage harvesting are the soil conditions, the number of trailers hauled by the truck following the harvester and the initial cost of the harvester (Hassuani *et al.*, 2005). As with balers, forage harvesters are not designed to handle sugarcane residue and therefore their reliability, when used to collect sugarcane residue, is lower than when used with forage crops. In order to address this limitation, a company called Cenicaga developed a special purpose attachment for a Claas-Jaguar 355 kW forage harvester, which helps it deal with the sugarcane residue better (Amu *et al.*, 2005).

Currently, there are no costs of performance available for the operation of a forage harvester. However, it is known that forage harvesters have been used in residue recovery trials on the Big Bend Sugar Estate in Swaziland (Domleo, 2013). Further investigation is required, to determine whether this method of residue recovery is economically feasible.

2.4.3.3 Silage wagon (Routes B and C)

A silage wagon can be used to collect sugarcane residue. The residue is first raked into windrows, after which the silage wagon can collect the residue. A silage wagon acts by picking up the residue and storing it in a storage bin on the wagon. The residue is compressed to approximately double the bulk density of the residue collected by a forage harvester (Hassuani *et al.*, 2005).

As with a forage harvester, a silage wagon has a recovery efficiency of approximately 70% (Hassuani *et al.*, 2005). Some factors which affect the cost of using a silage wagon are the distance from the field to a transloading zone, as well as soil conditions and the initial cost of the wagon (Hassuani *et al.*, 2005).

A common problem encountered with residue recovery equipment is their inability to handle sugarcane residue, and silage wagons have the same problem. There are currently no performance evaluation results for silage wagons available, but it is known that they have been tested on the Big Bend Sugar Estate in Swaziland (Domleo, 2013). Further investigation is required to determine whether this method of residue recovery is economically feasible.

2.4.3.4 Vibration in transport trucks

The use of vibration to increase the bulk density of sugarcane residue has been investigated. However, care needs to be taken, as the vibrations of the sugarcane bins may cause structural damage. The investigation found that, whilst this strategy has a high labour cost, it provides significant savings to the industry (Corporation, 2011).

2.5 Processes to Increase Bulk/Energy Density

Two of the major issues affecting the viability of bioenergy projects are the low energy density and the dispersed nature of the biomass. If pre-processing were undertaken, this could increase the energy density of the biomass and, subsequently, the transport and storage costs for the biomass will be reduced (Hobson, 2009). The two values referred to in this section include the bulk density (55 kg/m^3) and energy density (16.7 GJ/t or 0.92 GJ/m^3) of loose residue.

The processes reviewed in this section include torrefaction, pelleting and a combination of torrefaction and pelleting (TOP). Three other processes which were identified are pyrolysis, gasification and biodigestion; however, these are not discussed further, as they were deemed to be not applicable to this study. Pyrolysis produces bio-oil which cannot be utilised as a fuel, given the existing structures which are in place at the mill (Lyne, 2013). The objective of this study is to find methods of recovering sugarcane residue for utilisation as fuel. Biodigestion and gasification create other fuels from the residue and are therefore not applicable.

2.5.1 Torrefaction

Torrefaction is a pyrolysis process, which is a thermal process that increases the energy density of biomass by transforming the biomass into biochar. The process also increases the hydrophobic nature of the biomass, which means that moisture has less effect on the biomass. The transport and storage economics for the biomass are improved as a result of the increased energy density and bulk density (Hobson *et al.*, 2006; Uslu *et al.*, 2008). Torrefied biomass is very similar to coal, both in terms of handling characteristics and heating value (Hobson, 2009).

During torrefaction, biomass is placed in an inert environment (no oxygen) at temperatures between 250-350°C for a time period of 15-90 minutes (Hobson, 2009; Koppejan *et al.*, 2012). During this time, the fibrous structure of the original biomass is broken down, leading to a lower mechanical strength. The torrefied biomass is therefore easy to grind (Uslu *et al.*, 2008; Koppejan *et al.*, 2012). It has a mass equivalent to 70% of its original mass, but still holds approximately 90% of the original energy held in the biomass (Uslu *et al.*, 2008; Wang *et al.*, 2013). The biomass therefore has approximately the same calorific content as before the process, but the heating value per unit volume increases by a factor of ≈18 (0.92 to 18 GJ/m^3) (Uslu *et al.*, 2008). The further densification of the torrefied biomass is desired, especially if the torrefied biomass is to be transported over a long distance (Hobson, 2009). Other reasons for further densification include its low mechanical strength, its density of approximately 180-300 kg/m^3 and also the increased levels of dust (Uslu *et al.*, 2008).

During torrefaction, it is important to keep the temperature in the desired range, because char yield is a function of the process temperature. Three-hundred degrees Celcius is the optimum temperature, with higher temperatures leading to lower char yields (Table 2.7) (Asadullah *et al.*, 2007).

Table 2.7 Effect of temperature on bagasse pyrolysis output (Asadullah *et al.*, 2007)

Temperature (°C)	**Total Yield of Bio-oil (% weight)**	**Char Yield (% weight)**	**Gas Yield (% weight)**
300	18.66	77.00	4.34
350	51.32	43.80	4.87
400	60.66	31.93	7.41
450	65.47	26.26	8.27
500	66.13	24.86	9.01
550	30.63	24.66	14.71
600	59.52	22.86	17.82

There are several advantages to the torrefaction process, including a low technical risk during the process due to the relatively mild thermal requirement. There are also relatively low development and demonstration costs (Uslu *et al.*, 2008). Moreover, torrefaction will have a rapid development trajectory following its optimisation, as all the required technology is available. It also adds flexibility to the feedstock supply chain, as torrefied biomass can be easily pelleted (Hobson, 2009).

The main advantage of torrefaction is increasing the transport efficiency of the biomass. Studies including distances of up to 210 km, suggest that there would be further reductions in costs, if the torrefied biomass were to be transported over distances greater than 210 km (Hobson, 2009). It has been found that it is more cost-efficient to have many small-scale torrefaction plants, rather than a centralised pre-processing plant (Meyer *et al.*, 2012). Some torrefaction plants can process large particles and others small particles, but not many can do both efficiently. It is therefore important to decide on the type of torrefaction equipment required. This will impact the initial costs and the operating costs of the plant (Koppejan *et al.*, 2012).

Torrefied biomass can be used in a number of applications. The obvious application for this study is the use of the torrefied biomass at a sugar mill for the cogeneration of electricity. Other uses include using the biomass for co-firing with coal in pulverised coal-fired power plants, using the biomass for direct combustion or in the gasification process (Koppejan *et al.*, 2012).

If torrefied biomass, rather than loose biomass, is used for gasification, it can reduce the power consumption during the gasification process by up to 85% (Uslu *et al.*, 2008). At present, there is no practical knowledge concerning the limitations of using torrefied biomass for gasification (Koppejan *et al.*, 2012).

Torrefaction is a promising process which will be utilised in future biomass processing operations (Ruhul Kabir and Kumar, 2012; Svanberg *et al.*, 2013; Wang *et al.*, 2013).

2.5.2 Pelleting

The process of pelleting produces a product which is both uniform and stable. The pelleted biomass has a higher bulk density (575 kg/m^3) and a much higher energy density (10.18 GJ/m^3), compared to the original biomass. Moreover, there is less dust produced when handling pelleted biomass than when handling the original biomass. An additional positive attribute is that pelleted biomass is free-flowing and can be moved pneumatically. This free-flowing nature helps with the loading and unloading operations and this improves the transport efficiency of the biomass, as well as its storage efficiency (Erlich *et al.*, 2006; Uslu *et al.*, 2008).

There are four main processes involved in the pelleting technique. These include drying, grinding, pelleting and cooling (Ras, 2014). The highest temperature attained during pelleting is approximately 150°C. The biomass which is being pelleted should have a moisture content of between 10-25%, as this is considered the optimum moisture content range (Uslu *et al.*, 2008; Ras, 2014). If the moisture content is outside of this range, then the pressure required during the process increases significantly (Uslu *et al.*, 2008). A study by Sultana *et al*. (2010) found that the net calorific heating value for wood pellets varies significantly, as the moisture content of the biomass varies.

A problem which may be encountered at a pelleting station is heat generation in the pellet channels. This can result in a fire or dust explosion risk (Koppejan *et al.*, 2012). When compared to wood pellets, the sugarcane industry has very little experience with regards to pelleting sugarcane biomass (Erlich *et al.*, 2006).

Boevey (1983) studied the production of sugarcane residue pellets and found that the pellets were fragile and broke easily, forming a fine dust. Sugarcane residue has a high fibre content, which requires a high compaction rate. In turn, this results in the undesirable generation of excess heat (Boevey, 1983).

2.5.3 TOP

The technology exists where the processes of torrefaction and pelleting are combined (TOP), to produce an output material which has a significantly higher energy density of approximately 22 MJ/kg (Uslu *et al.*, 2008). By pelleting torrefied biomass, power consumption during pelleting can be reduced by between 70–90%, compared to conventional biomass pelleting (Uslu *et al.*, 2008). Pelleting does have a lower process efficiency than torrefaction and this is attributed to it having a high initial energy input associated with grinding and the pelleting process (Hobson, 2009). Studies have concluded that it is advantageous to use torrefaction and pelleting as a combination, rather than using either torrefaction or pelleting individually (Uslu *et al.*, 2008).

2.5.4 Comparison of processing treatments

Table 2.8 contains a comparison of the three pre-processing techniques discussed above. The study conducted by Uslu *et al.* (2008) found that the optimal energy chain is the use of TOP biomass to create power at an existing co-firing facility (Uslu *et al.*, 2008).

Table 2.8 Comparison of torrefaction, TOP and pelleting (Uslu *et al.*, 2008)

	Torrefaction	**TOP**	**Pelleting**
Process efficiency (%)	92.0	90.8	84.0 – 87.0
Energy content (LHV_{dry}) (MJ/kg)	20.4	20.4 - 22.7	17.7
Bulk density (kg/m^3)	230	750 - 850	500 - 650
Energy density (GJ/m^3)	4.6	14.9 - 18.4	7.8 - 10.5

Although torrefaction does seem like a very promising and efficient process for minimizing costs and improving energy use, it has not yet been practically demonstrated and its performance has not been confirmed. Pelleting, however, is a proven technology, although there is room for improvement, thus it is an important option for pre-processing (Uslu *et al.*, 2008).

2.6 Economics of Residue Recovery Systems

This section contains a review of the economics of the above-mentioned residue recovery methods.

2.6.1 Chopper harvester routes

Braunbeck *et al.* (1999) found that the cost for manually harvesting and loading burnt sugarcane was approximately double the cost of mechanical harvesting. The same cost difference was found for green sugarcane harvesting.

Norris (2008) came to the following conclusions when considering Route A (where the sugarcane is cut whole stalk and separated from the residue at the mill). If the sugarcane industry is currently implementing burnt sugarcane harvesting, a move to green sugarcane harvesting will result in the cost of residue collection being in excess of the value of the residue. The reason for the increase in cost is the lower bulk density of the sugarcane because of the residue, which increases the transportation costs. This is not economically viable and more research needs to be done, if Route A is to be used.

In 2005, Marchi *et al.* (2005) created an economic model which compared three different sugarcane harvesting and residue recovery routes. These routes are represented by Route C, Route D and Route E, which are detailed in Section 2.4. Table 2.9 contains results from the model. If Route D was taken as the baseline route, the cost of residue recovery for Route C is 59% of that for Route D and for Route E it is 44% of that for Route D. The study concluded that Route E was the most economical option of the three routes. The reason for this is that the residue is not only used at the mill, but also for its agronomic benefit in the field. This conclusion corresponds with the results found by the SRDC (2011), which tested the feasibility of using a shredder fan in a harvester, whilst implementing Route E.

Table 2.9 Residue characteristics for each route (Marchi *et al.*, 2005)

Items	Baseline	Route C	Route D	Route E
Residue in sugarcane field (t)	180 697	180 697	180 697	180 697
Residue transported with sugarcane (t)	43 909	43 909	170 759	127 934
Residue on the ground after harvesting (t)	136 788	136 788	9 938	52 764
Baled residue (t)	-	114 902	-	-
Residue left in the field (t)	136 788	21 886	9 938	52 764
Residue removed by the cleaning station (t)	-	-	119 531	89 554
Total residue available at the mill (t)	-	114 902	119 531	89 554

2.6.2 Infield residue collection

The results from a study conducted by de Carvalho Macedo *et al*. (2001), which investigated the expenditure of the baling operation, from the field to the mill, are summarised in Table 2.10. The study took into account the entire baling process, from raking to the shredding at the mill, including the agricultural impacts of removing the residue. According to Norris (2008), the cost per unit energy of the baling operation is approximately 50% of that for coal, which is considered low for a solid fuel and this is why baling sugarcane residue is being considered as a viable source of energy for power generation.

Table 2.10 Cost at the mill of baled residue by Route C (de Carvalho Macedo *et al.*, 2001)

Operation	Percentage of Total Cost
Raking	3.3
Baling	21.6
Bale handling in the field	6.6
Bale loading	8.0
Bale transportation	10.7
Bale unloading	2.9
Partial cost	**53.0**
Agricultural cost	42.2
Residue shredding	4.8
Total cost	**100.0**

2.6.3 Residue processing techniques

Meyer *et al.* (2012) conducted a study into the viability of processing biomass which found that the delivery costs were the lowest for raw biomass, for haulage distances below 240 km, whilst for distances over 240 km, the delivery costs were the lowest for torrefied biomass (Figure 2.5). In addition, it was found that it was more expensive to deliver pellets, compared to torrefied biomass, at distances greater than 200 km (Meyer *et al.*, 2012).

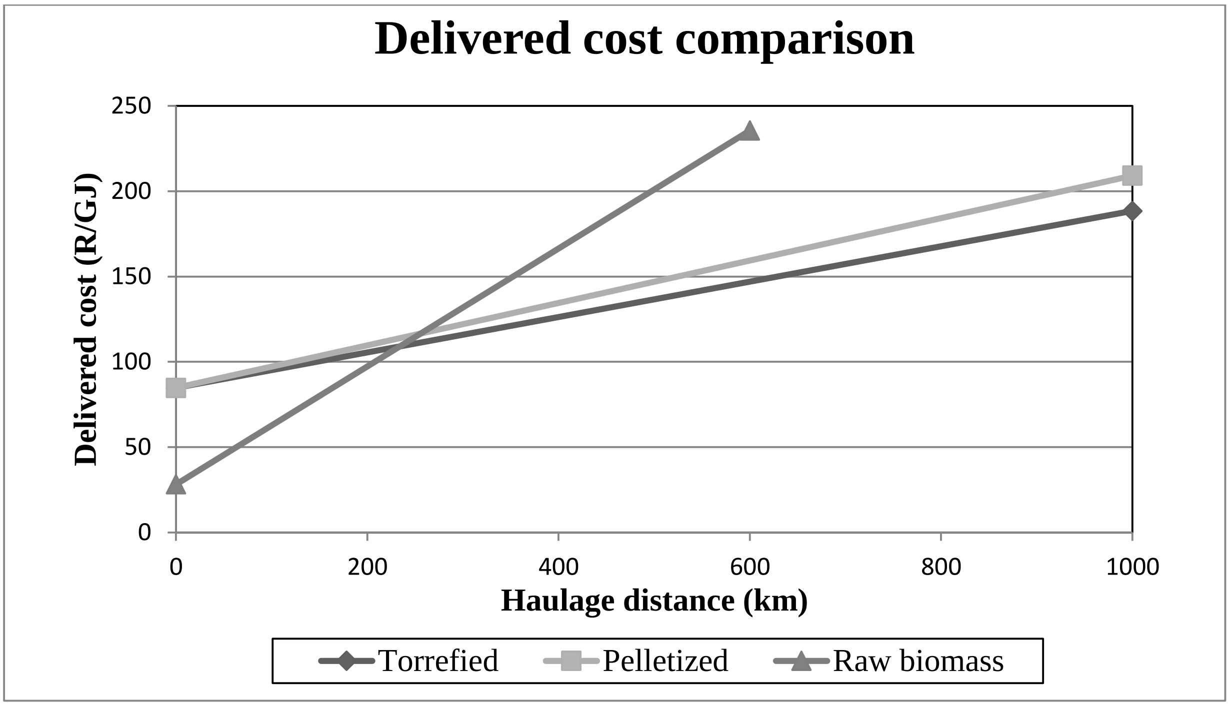

Figure 2.5 A comparison of the delivered costs for 50 kilotons (kt) of torrefied, pelletized and raw biomass (AUD $ 1 = R 9.42) (Meyer *et al.*, 2012)

2.7 Discussion and Conclusions

Section 2.4 contains a review of the different systems and methods of recovering sugarcane residue from the field and transporting it to the mill. Five possible recovery routes were investigated. Routes A and B involve whole-stick harvesting, whilst Routes C, D and E involve the use of a chopper harvester. There are no monetary costs available for residue recovery under South African conditions, but costs from a study in Australia were acquired and will be discussed. This will help give a better understanding of the economic feasibility of the different residue recovery methods. It is important to remember that the value of residue at an Australian mill in the year 2008 was estimated at R 350/t (AUD $ 1 = R 9.42).

Route A was only found to be economically feasible if it were implemented in an area where green sugarcane harvesting is currently being employed, costing approximately half the value of residue. However, this is rarely the case in South Africa, as burnt sugarcane harvesting is widely used, and thus the additional cost of changing to green sugarcane harvesting will make the cost of this route approximately 159% that of the value of residue. Another investigation found that of Routes C, D and E, Route E would be the most economical, costing approximately 36% that of the value of residue. In South Africa, over 90% of the sugarcane is harvested manually and this route would therefore not currently be appropriate for the South African sugar industry, but should still be further investigated as the industry may change in time.

If the residue is to be left in the field to be recovered in a second operation, it can either be collected by baling, by using a silage wagon, or by using a forage harvester to place it in a trailer for transport. The cost of baling sugarcane residue in Australia has been estimated at approximately 50% that of the value of residue. This is a competitive price. There are no values for the cost of recovering sugarcane residue using a silage wagon or a forage harvester, but these methods do seem to have potential and should be investigated further.

The sugarcane residue could be processed in an effort to reduce transportation costs. This would increase the bulk density of the residue, as well as significantly increasing its energy density. Of the three processes considered, TOP residue has the highest energy density (18.4 GJ/m^3), whilst the energy densities for torrefied or pelleted sugarcane residue are still higher than that of loose residue and, therefore, all three of these processes should be investigated further.

It is important to realise that many of the values used in this literature review were obtained from research which was conducted throughout the world. These values can be site-specific i.e. the sugarcane variety and soil conditions may be very different to those which are experienced in South Africa. The cost structures are also dependent on the local conditions. Therefore, these values may not be applicable to the sugarcane industry in South Africa. The residue recovery methods that will be investigated further should be evaluated under South African conditions, in order to eliminate this source of error. The growing conditions in South Africa also need to be considered, as they can vary greatly. Sugarcane which is grown near the coast is generally harvested in 12-month cycles, whilst sugarcane, which is grown inland, is harvested in 24-month cycles. The expected yield for inland and coastal areas does vary.

The recovery methods that could be applicable in South Africa, and which should be investigated further, are Routes A and D, where the residue is separated from the sugarcane at the mill, Route B and C, where the residue is left infield, and also Route E, where there is partial cleaning of the sugarcane. The baling of sugarcane residue and the use of a forage harvester or silage wagon to recover residue should also be investigated, as well as the pre-processes of torrefaction, pelleting and TOP. These methods show the greatest promise and have the potential to work under South African conditions. Only manual harvesting will be considered for the recovery routes involving whole-stick harvesting, as mechanical whole-stick harvesting is not a common practice in South Africa.

This literature review contained a comprehensive investigation of the different methods and routes by which sugarcane residue can be recovered from the field and transported to the mill. Each method has been discussed in depth and the methods which should be investigated further have been stated. The relative economics of each method have been discussed.

3. MODEL SELECTION

In order to estimate the cost of sugarcane residue recovery and the effects of having a residue blanket on the soil, either an existing model needs to be selected and adapted for this project, or a new model needs to be developed.

3.1 Models Considered

In order to decide whether a new model needs to be developed, or an existing one adapted, a short review of the available models was required.

An investigation into the framework required for integrating a complex harvesting and transport system for sugar production was conducted in Australia (Higgins *et al.*, 2004). In this study, the sugar industry was divided into four major operations, namely, growing, harvesting, transport and milling. The study made use of two existing stand-alone models, which modelled two of the four major operations. Separate models were developed for the remaining two operations. The reason why separate models were used for each operation was because it was not regarded as being feasible to build one 'super-model' to describe and optimise the whole system.

A model was developed in Australia called the Harvest Haul Model, which quantifies the performance of the harvesting sector on a regional scale (Sandell and Prestwidge, 2004). The model can then be integrated with other component models, similar to the model by Higgins *et al.* (2004), to provide the capability of modelling the whole sugar system. The Harvest Haul Model is a database application which can determine an approximate cost of harvesting for singular blocks of sugarcane on a farm. A similar study was undertaken by Thorburn *et al.* (2007), which integrated four single-sector models to model the biophysical feasibility and financial attractiveness of whole-crop harvesting, to maximise electricity generation. The four single-sector models, which were integrated together, cover the four sectors of production, harvest, transport and the mill. A further model was developed by Thorburn *et al.* (2006), which followed the same principle of dividing the sugar supply chain into different sectors, and modelling each sector singularly, after which these singular models were integrated together. The reason this was done in this study, was to create a model which was user-friendly to users who were outside the research group.

A study was conducted in Australia, which attempted to simulate the effects of residue and N fertilizer management on soil organic matter levels and yields of sugarcane. As long-term data on the effects of these practices is difficult to find, this study made use of a model called CENTURY. This model was used to study the long-term effects of sugarcane residue management on soil organic matter levels, nitrate leaching, crop yields and N mineralization (Vallis *et al.*, 1996). In Columbia, a computer model was developed to help monitor costs involved with recovering sugarcane residue. This model, termed PARCA, was developed, using cost allocation techniques, push and pull techniques and logistics (Amu *et al.*, 2005).

An economic model, which took into account several levels of detail which could affect the final cost of biomass, was developed in Brazil. This model was developed during a study titled "Biomass Power Generation: Sugarcane Bagasse and Residue" (Marchi *et al.*, 2005).

The South African Sugarcane Research Institute (SASRI) developed a model to compare the economics of harvesting burnt and green sugarcane. This model is referred to as the Economics of Sugarcane Production and Transport Calculator (EconoCane), formerly known as the Economics of Trashing Decision Support Program (DSP) (Wynne and van Antwerpen, 2004). The objective of this model was to create a tool which could help extension officers, growers and researchers to find the most efficient sugarcane harvesting practice. This model is a singular model that incorporates each sector of the sugarcane supply chain, from the agronomics to the harvesting operation, to transport and to the mill. This model was developed specifically for the South African sugar industry.

3.2 Selected Model

EconoCane, developed by Wynne and van Antwerpen (2004), and further developed in 2008 (van Antwerpen *et al.*, 2008) and in 2012 (Smithers, 2012), was chosen to be adopted and adapted for this project, as it simulates many of the components of costing different residue recovery routes. It explicitly includes the simulation of the advantages to recovering sugarcane residue, but it is not always appropriate in all conditions (Wynne and van Antwerpen, 2004). The spreadsheet model is comprised of 18 sheets, which are summarised in Table 3.1. These sheets are interrelated and combined to find the final cost per ton of harvesting burnt and green sugarcane.

Table 3.1 Description of the sheets in EconoCane (Wynne and van Antwerpen, 2004; van Antwerpen *et al.*, 2008; Smithers, 2012)

Sheet Number	**Sheet Name**	**Sheet Objective**
1	Start	Provides a background to the model and an overview and instructions on how to use it.
2	Input	Lists 213 input values.
3	Mechanical inputs	Contains all input/costing information relevant to any piece of equipment used in the model.
4	Herbicide guide	Helps user to determine which herbicides to use, depending on soil conditions, and also whether it is applied pre- or post-emergence.
5	Herbicide Database	Contains all relevant input data regarding all herbicides used in sugarcane farming.
6	Herbicide inputs	Using inputs from the Herbicide Database sheet, this sheet can be populated. A 1st spray, 2nd spray and 3rd spray operations can be included.
7	Fertiliser inputs	Combinations of fertilizers used in the green versus burnt treatment scenario are specified in this sheet. Costs per ton of fertilizers are required inputs. The total cost (R/t) of fertilizer is then calculated.
8	Milling inputs	Contains input values acquired from the mill. These inputs are not included in Input sheet, as this table is sent to the mill, where it is populated.
9	Agronomics	Quantifies the costs associated with yield decline, spreading tops and residue, herbicides and fertiliser application.
10	Irrigation	Calculates irrigation cost for burnt and green sugarcane, and thus the cost reduction, by implementing green sugarcane harvesting. The difference between burnt and green sugarcane water requirements is the water saving which results from a residue blanket. Water cost, as well as operation costs, are added together, to find a total irrigation cost.
11	Delays	Given the harvesting and transport regime, the impacts of delays on sugarcane quality are calculated.
12	Losses	Given the impacts due to delays and the effectiveness of the residue recovery operation, the value of delivered sugarcane is calculated.
13	Manual Harvesting	Given the required labourers and equipment for manual harvesting, and a number of assumptions pertaining to how the sugarcane is harvested, the cost per ton to harvest burnt and green sugarcane is calculated.
14	Chopper Harvesting	Given the area to be harvested and the parameters pertaining to a chopper harvester, the harvesting cost per ton can be calculated. Infield transport requirements, as well as the number of harvesters required, are also calculated.

Sheet Number	Sheet Name	Sheet Objective
15	Baling	Given the area to be baled and the expected residue to be baled per hectare, the cost per ton of the baling operation, can be calculated. Infield transport, loading and road transport costs are calculated.
16	Transport	Given the impacts of delays and the transport regime used, the total cost of the transport operation is calculated.
17	Milling	The required milling capacity to crush the specific crop is determined and the cost of additional milling capacity is calculated.
18	Summary	Provides the economic summary for both burnt and green sugarcane harvesting scenarios and the difference in total Rands and Rands/hectare.

4. MODEL DEVELOPMENT AND ASSUMPTIONS

Chapter 2 outlines the various sugarcane residue recovery routes available and which of these would be most suitable for South African conditions. The three methods selected to be modelled for the collection of sugarcane residue from the field are the use of a baler, a forage harvester and a silage wagon. In addition to these sugarcane residue recovery methods, the processing of the sugarcane residue is modelled. The three processes modelled are torrefaction, pelleting and TOP. It was assumed that the sugarcane residue was taken to the mill to be used for cogeneration. In order to model these different sugarcane residue recovery routes, a number of factors need to be taken into account, including the use of machinery for residue recovery, infield transport, loader zone machinery and road transport. Before the model could be developed, each sugarcane residue recovery route was mapped, using the mind-mapping software (Mindjet, 2008).

The modelling was able to begin once each residue recovery pathway was mapped and the input values and processes involved for each pathway were included in the mind-map. The additional processes were added to EconoCane, which was developed in Excel. In this model, each operation within the harvesting process was assigned a sheet within the Excel spreadsheet. Some of the existing sheets from EconoCane were used, including the Chopper Harvesting, Manual Harvesting and Baling sheets. Five additional operations, or sheets, were added to the model, which are necessary to cost the different residue recovery routes. These sheets included Forage Harvesting, Silage Wagon, as well as the three residue processes of Torrefaction, Pelleting and TOP. These sheets are then summarised in a summary sheet to reflect the costs incurred from sugarcane harvesting to residue collection and delivery to the mill.

4.1 Mapping of Different Residue Recovery Routes

In order to synthesis the reviewed literature in Chapter 2, Mindjet MindManager 8 was used to create a mind-map that displays every residue recovery route. Each recovery route pathway is clearly outlined in the mind-map, which includes the costs and processes involved at each step in the pathway.

4.1.1 Sugarcane harvesting methods

Before the sugarcane residue can be collected, it first needs to be harvested. Sugarcane harvesting can be separated into two broad categories, namely, manual harvesting and mechanical harvesting. Manual harvesting can be classified as harvesting the sugarcane whole-stick and placing it either in windrows, or stacks or bundles. Mechanical harvesting refers to the use of a chopper harvester. The two sugarcane harvesting systems considered can be seen in Figure 4.1.

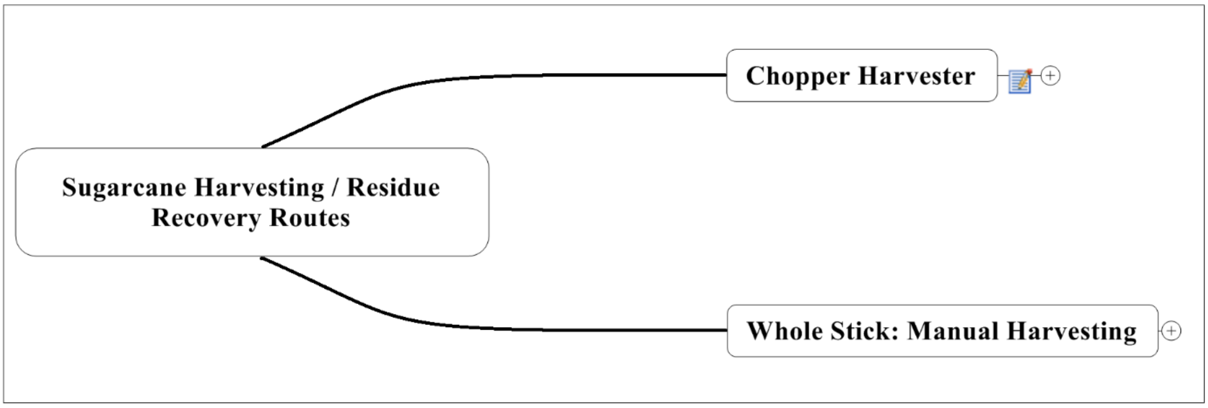

Figure 4.1 Harvesting systems considered

4.1.2 Separated at mill or infield

Figure 4.2 depicts how the residue can be separated from the sugarcane. It can either be separated infield, or, it can be transported with the sugarcane to the mill, where separation occurs. If the residue is separated infield, the residue which is recovered may include green residue, in contrast to when separation occurs at the mill, where dry residue (i.e. brown/dead residue) is collected. In addition, infield separation incurs further costs and involves more infield traffic, as the labour spends more time on each sugarcane stick. However, when the sugarcane is received at the mill, it will be clean and easy to process. If the residue is not removed from the sugarcane infield and dry residue separation is performed at the mill, this results in a higher percentage of dry residue being processed with the sugarcane, which can lower sugar yields, as the fibre in the dry residue absorbs some of the sugar during the sugar extraction process.

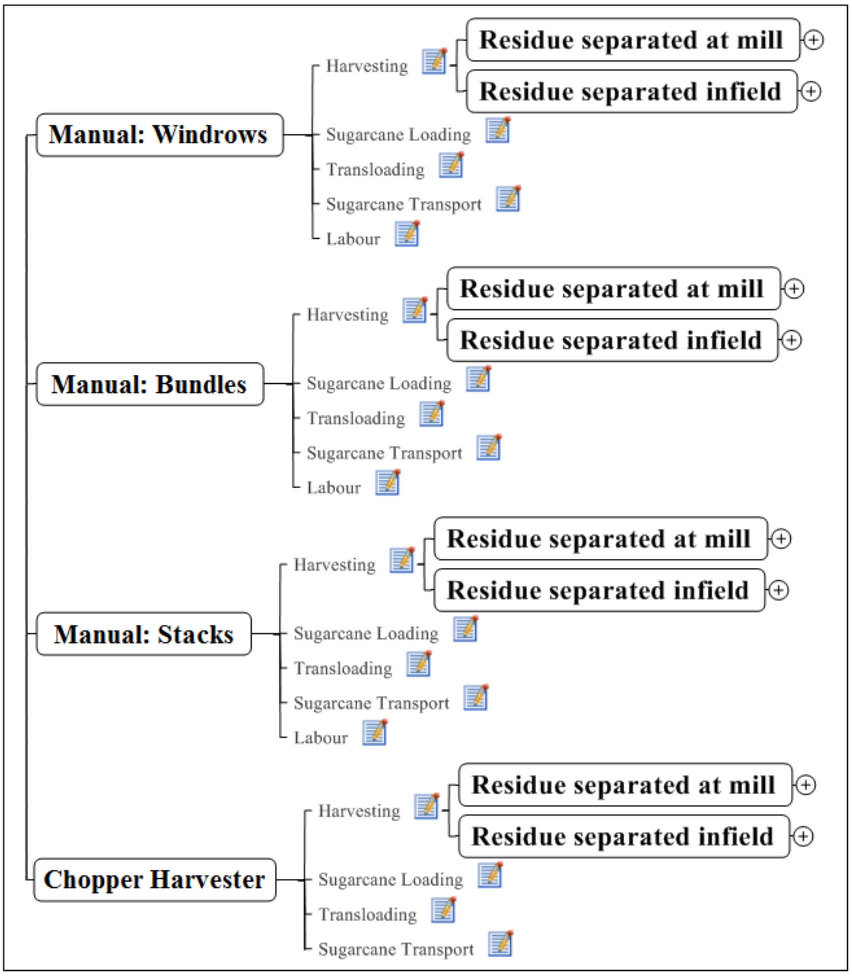

Figure 4.2 Residue separation at mill or infield

4.1.3 Residue recovery from field

If the residue has been removed from the sugarcane infield, then it will need to be recovered from the field. There are three residue collection methods which have been considered, as can be seen in Figure 4.3. These are the use of a baler, a forage harvester and a silage wagon.

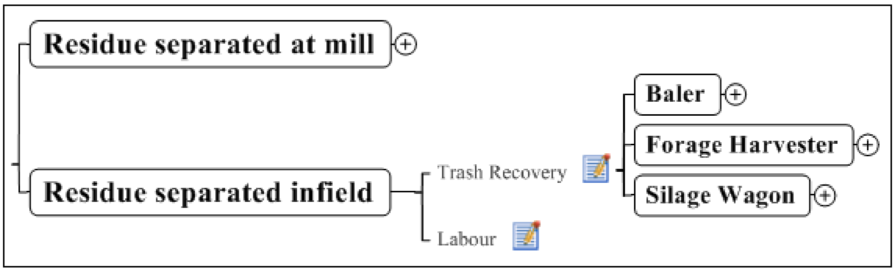

Figure 4.3 Residue recovery systems considered

4.1.4 Residue processing

After residue collection, the residue can either be transported to the mill or transported to a processing plant. Three processes were considered, namely, torrefaction, pelleting and TOP, as shown in Figure 4.4. The reason why these processes were considered was because they are able to decrease transportation and handling costs.

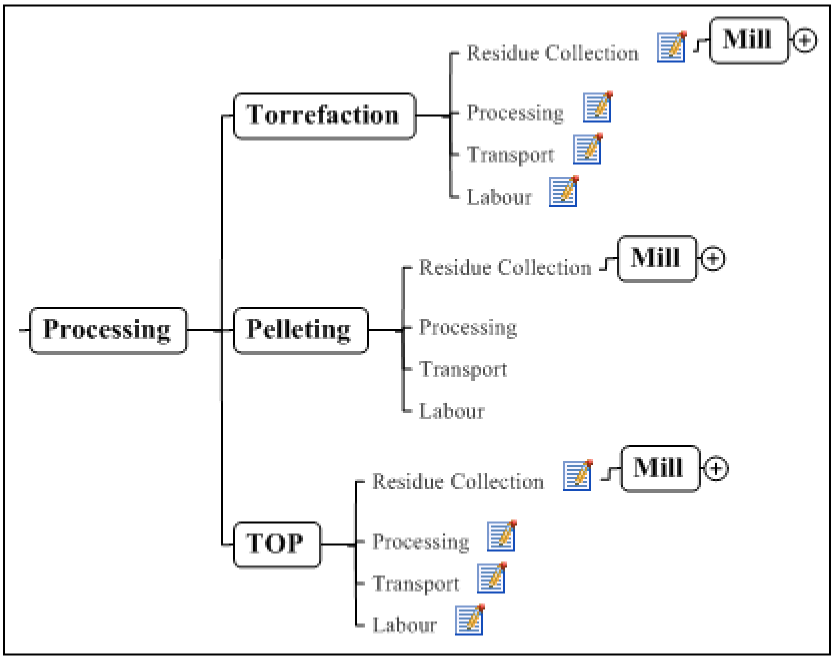

Figure 4.4 Residue processes considered

4.2 Costing

The costs involved with sugarcane residue collection do not only include the costs of the actual operation (i.e. operator wages, licenses and insurance, maintenance, fuel and electricity consumption), but also the machinery and their associated costs. The tables in this section cover all the costs associated with the many different pieces of equipment to be used in the model. This includes the machinery used in the Manual Harvesting, Chopper Harvester, Transport, Baling, Forage Harvester, Silage Wagon, Torrefaction, Pelleting and TOP sheets. These values are used to calculate the depreciation, interest, fixed costs, fuel costs, electricity costs and maintenance costs for each piece of machinery. Thus, when these costs are added together, the total cost per ton of residue/processed material is computed.

One issue which was encountered was the incomparable output costs involved with the different processes of a residue recovery route. The output cost for sugarcane harvesting was a cost per ton of sugarcane (R/t), whilst the output cost for residue recovery was a cost per ton of residue (R/t). The output cost for sugarcane residue processing is a cost per ton of processed residue (R/t). Thus, when finding the cost for any residue recovery route, these costs cannot simply be added together. The way in which this was dealt with is explained in Section 4.4.

4.2.1 General calculation

A number of costing equations were utilised for all equipment used in this model. The required input values for each equation are described below, whilst the actual equations can be found in Appendix B. The total cost for each piece of equipment comprises of the following five elements:

- fixed costs,
- tyres,
- maintenance,
- fuel consumption, and
- electricity consumption. (Technologists, 2004; Barry and Ellinger, 2012)

Some of these may not be required in some sheets i.e. electricity consumption in the baling sheet; however, they are all taken into account. Equations from ISSCT (2004) and Barry and Ellinger (2012) are applied to calculate the costs described in this section. These equations can also be found in Appendix B. To determine the fixed annual costs, four values are required:

- operator wage,
- license and insurance,
- depreciation, and
- interest. (Technologists, 2004; Barry and Ellinger, 2012)

The following are required to compute the depreciation of a piece of machinery:

- purchase price,
- actual resale value, and
- actual life. (Technologists, 2004; Barry and Ellinger, 2012)

The following are required to compute the interest on a piece of equipment:

- purchase price,
- actual resale value, and
- interest rate. (Technologists, 2004; Barry and Ellinger, 2012)

The interest rate was taken as 5.5% (Triami Media, 2014). The tyre cost per year is determined using the following inputs:

- original purchase price of the tyres,
- expected life (yr), and
- operating hours per year. (Barry and Ellinger, 2012)

The fuel expenditure per year requires the following:

- fuel consumption (l/h),
- operating hours per year, and
- fuel price (R/l). (Barry and Ellinger, 2012)

The fuel cost was taken as R 13.29 per litre (Engen, 2014). The electricity consumption per year requires the following input values:

- electricity consumption (kWh/t_{input}),
- electricity price (R/kWh),
- operating hours per year, and
- total input tons per year. (Barry and Ellinger, 2012)

The electricity price was taken as 0.54 R/kWh (Eskom, 2013; Bezuidenhout, 2014b). The maintenance value comprises of the following:

- purchase price,
- life of the equipment,
- percentage of the purchase price set aside for maintenance per year, and
- operating hours per year. (Technologists, 2004; Barry and Ellinger, 2012)

In order to calculate the above costs, costing data are required for each piece of equipment used in the model. The way in which this data was determined is explained in the sections that follow. The input data required for each piece of equipment is listed below:

- Purchase price (R),
- Interest rate (%),
- Operator (R/yr),
- License and insurance (R/yr),
- Life (h),
- Tyres: Price (R),
- Tyres: Life (h),
- Electricity usage (kWh/t_{input}),
- Maintenance: % purchase price,
- Maintenance: Maximum life (yr),
- Resale: Base %,
- Resale: Base age (yr),
- Resale: Yearly %, and
- Resale: Minimum price (%).

4.2.2 Infield operations

A selection of tractors, rakes and infield trailers are available for use in the infield operations in this model. The costing values for these pieces of equipment were found in the Guide to Machinery Costs (Lubbe *et al.*, 2013). There is a choice of 17 tractors, eight agricultural trailers and one rake. Their input costing values can be found in Table 4.1. As indicated in Table 4.1, some of the data can vary. This depends on the choice of tractor or trailer.

4.2.3 Loading and road transport

A selection of bell and slew loaders, road haulage trucks and road haulage trailers is available in this model. The costing values for these pieces of equipment can be found in the Guide to Machinery Costs (Lubbe *et al.*, 2013). There is a choice of six loaders, five road haulage trucks and four road haulage trailers included in the model. Their input costing values can be found in Table 4.2. As indicated in the Table, some of the data can vary. This depends on which type of tractor or trailer is chosen.

Table 4.1 Costing data: Agricultural tractors, agricultural trailers and rake (Lubbe *et al.*, 2013)

Cost Component	**Agricultural Tractor**	**Agricultural Trailer**	**Rake**
Purchase price (R)	210 000 - 1 470 000	85 000 - 610 000	18 000
Operator (R/yr)	32 500 – 56 000	0 – 27 800	0
License and insurance (R/yr)	0.5 - 4% purchase price	1 - 2% purchase price	1% purchase price
Life (h)	10000 - 12000	12000 - 15000	2000
Tyres:-			
Price (R)	11 120 – 70 800	7 800 – 46 400	0
Life (h)	3000 – 4000	3000 – 4000	0
Fuel :-			
Consumption (l/h)	4 - 17	0	0
Maintenance:			
% Price	80 - 100	30 – 45	60
Max. life (yr)	15	15	15
Resale :-			
Base %	40	10	35
Base age (yr)	5	10	5
Yearly %	2	2	5
Minimum price (%)	12	10	10

Table 4.2 Costing data: Loaders, road haulage trucks and trailers (Lubbe *et al.*, 2013)

Cost Component	**Loaders**	**Road Haulage**	**Road Trailer**
Purchase price (R)	580 000 - 1 500 000	525 000 - 1 140 000	395 000 - 550 000
Operator (R/yr)	27 600 – 33 000	48 500 – 79 000	0
License and insurance (R/yr)	1% purchase price	8% purchase price	4% purchase price
Life (h)	10000 - 12000	400000 - 700000	700000
Tyres:-			
Price (R)	9 200 – 57 000	32 400 – 56 000	42 400 – 84 800
Life (h)	3000 - 4000	75000 - 100000	150000
Fuel :-			
Consumption (l/km)	5 - 14	0.28 – 0.70	0
Maintenance:			
% Price	80	80 – 100	30
Max. life (yr)	15	15	15
Resale :-			
Base %	40	40	30
Base age (yr)	5	5 – 6	10
Yearly %	5	5	2
Minimum price (%)	10	15 - 20	10

4.2.4 Sugarcane residue collection

The costs related to both forage harvesters and silage wagons were obtained from Tweddle (2013). The costing data relating to balers was obtained from the Guide to Machinery Costs (Lubbe *et al.*, 2013). Both these sources were used to populate Table 4.3.

In total, there were 12 forage harvesters available in the Guide to Machinery Costs (Lubbe *et al.*, 2013). The costing data specific to each harvester were incorporated into the Economics of Trashing DSP. There were no 'silage wagons' in the costing guide, but after communication with Tweddle (2013), it was confirmed that using the costing data for 'feed mixers' would be a reasonable substitute for silage wagons. In total, there were five feed mixers available in the costing guide, with the relevant data for each wagon incorporated into the Economics of Trashing DSP (Lubbe *et al.*, 2013). There were 10 balers available for selection.

Table 4.3 Costing data: Forage harvester and silage wagon (Lubbe *et al.*, 2013; Tweddle, 2013)

Cost Component	Baler	Forage Harvester	Silage Wagon
Purchase price (R)	71 000 - 1 676 546	92 790 - 581 250	375 330 - 889 930
Operator (R/yr)	0	0	0
License and insurance (R/yr)	1% purchase price	1% purchase price	1% purchase price
Life (h)	2250	2000	6000
Tyres:-			
Price (R)	3 000	14 600	20 000
Life (h)	3000	3000	3000
Fuel :-			
Consumption (l/h)	0	0	0
Maintenance:			
% Price	130	80	60
Max. life (yr)	5	15	15
Resale :-			
Base %	10	35	10
Base age (yr)	2	5	10
Yearly %	10	5	2
Minimum price (%)	10	10	10

As indicated in Table 4.3, some of the data can vary. This depends on which type of tractor or trailer is chosen.

4.2.5 Sugarcane residue processing

As with the above-mentioned operations, the basic costing values in Table 4.4 were required. The values which were utilised and the way in which these values are derived are explained below. The capital costs have not been included in Table 4.4, as these costs vary, depending on the output of the processing plant. The way in which the variable capital costs were calculated, is described in Sections 4.2.5.1, 4.2.5.2 and 4.2.5.3.

Schmitz (2013), who is the Chief Operating Officer at Meadow Feeds in KwaZulu-Natal, indicated that an operator at a pelleting plant will earn a salary of R 8200 per month (45 hours/week). It was assumed that this wage would be the same for a TOP and torrefaction plant. The total operating cost per annum was calculated by dividing the monthly wage by the number of hours each month (180 hours) and then multiplying this by the total machine hours per year. License and insurance was taken as 0.5% of the purchase price per annum (Svanberg *et al.*, 2013).

Table 4.4 Costing data: Pelleting, TOP and torrefaction plants

Cost Component	Pelleting	TOP	Torrefaction
Capital cost (R)	-	-	-
Operator (R/yr)	250 000	250 000	250 000
License and insurance (R/yr)	0.5% capital cost	0.5% capital cost	0.5% capital cost
Life (h)	74131	74131	74131
Electricity :-			
kWh/t_{input}	129	102	92
Maintenance:			
% Price	5 - 18	5	5
Max. life (yr)	15	15	15
Resale :-			
Base %	0	0	0
Base age (yr)	0	0	0
Yearly %	0	0	0
Minimum price (%)	10	10	10

The electricity consumption for the plant was taken as 92 kWh/t_{input} for the torrefaction plant, 102 kWh/t_{input} for the TOP plant and 129 kWh/t_{input} for the pelleting plant (Uslu *et al.*, 2008). The percentage of the initial capital cost of the plant for maintenance per year was taken as 5% for a TOP and torrefaction plant, but for a pelleting plant the maintenance percentage varied, according to the different components of the plant. The percentage was taken as 5%

for the grinding unit, dryer, feeder, boiler and cooler, as well as for bagging and conveying (Uslu *et al.*, 2008), whilst it was taken as 18% for the hammer mill and 10% for the pellet mill (Sultana *et al.*, 2010).

The maximum life of each plant was taken as 15 years (Uslu *et al.*, 2008; Smithers and Lyne, 2013). The life (hours) of the plant is calculated by using the maximum life (years) and the total machine hours per year. As the plant will probably not be sold, resale values for the plant, including the base percentage, base age and yearly percentage, were taken as 0% (Smithers and Lyne, 2013). The one resale value which was considered, was the minimum price. It was assumed that if the plant was disassembled, the machinery and scrap from the plant would be able to be sold off as scrap and a minimum of 10% of the initial purchase price could be recovered (Smithers and Lyne, 2013).

The way in which the capital costs were calculated for each processing plants is described in the following sections.

4.2.5.1 Pelleting plant

Four journal articles were found pertaining to the costing of a pelleting plant. The capital cost for a pelleting plant size of 40 Megawatts/ton/hour was reported as 6.2 million Euros by Uslu *et al.* (2008), as 6 million Euros by Nilsson *et al.* (2011), as 2.4 million Euros by Sultana and Kumar. (2012) and as 19.5 million US Dollars by Koppejan *et al.* (2012). The problem with these capital costs was that inaccuracy was introduced when they were converted to South African Rands, as they were acquired in the years 2008, 2011 and 2012. In addition, if these capital values are converted directly into South African Rands, using the current exchange rate, the resulting Rand values are exorbitant and unrealistic for South Africa. Thus, an indirect method of establishing the Rand costs was developed, as described below. Eksteen (2013) provided the capital cost for a range of production rates, as listed in Table 4.5.

Table 4.5 Pelleting plant capital requirements (Eksteen, 2013)

Production Capacity (t/h)	**Production Capacity (kt/yr)**	**Purchase price (Rand × 10^6)**
0.2	0.9926	0.18
0.5	2.4816	0.22
1.0	4.9632	0.34
1.5	7.4448	0.38
2.5	12.4080	0.75

Using the values from Table 4.5, a relationship between the purchase price and production capacity can be derived, as shown in Figure 4.5. An economy of scale relationship was expected; however, for the data which was available, a linear relationship is evident. This is explained further in a discussion in Section 7.1.

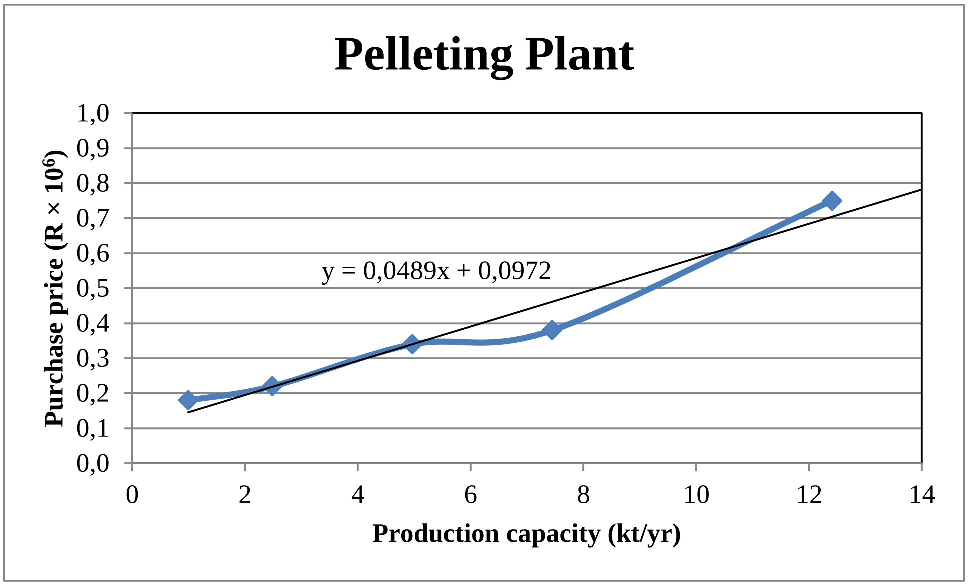

Figure 4.5 Relationship between purchase price and production capacity for a pelleting plant (Eksteen, 2013)

Equation 4.1 was used in the model to calculate the capital cost of a pelleting plant in millions of South African Rands (Figure 4.5). This equation allowed the cost to vary, depending on the expected production capacity of the plant, and therefore gives an accurate estimation.

$$P_{pellet} = 0.0489 y_{pellet} + 0.0972 \quad (4.1)$$

where

P_{pellet} = purchase price [R × 10^6] for pelleting plant, and

Y_{pellet} = plant production capacity [kt/h].

The economy-of-scale relationship is not a realistic relationship, as there will always be an economy-of-scale relationship when setting up any sort of plant; however, this is the best available information.

4.2.5.2 TOP plant

Four journal articles were found that were related to the costing of a TOP plant. They had varying capital costs for the setup of a TOP plant. Svanberg *et al.* (2013) used a capital cost for a TOP plant at 45.5 million Euros for a plant processing capacity of 200-240 kt/yr. For a plant processing capacity of 60 kt/yr, Uslu *et al.* (2008) used a cost of between 5.2 and 7.8 million Euros, whilst for the same plant capacity, Nemeth (2009) used a plant cost of 11 million Euros. Koppejan *et al.* (2012) used a plant cost of 24 million US Dollars for a plant capacity of 100 kt/yr. For the same reasons as given for pelleting plants, a South African capital cost for a TOP plant was required. TOP is a relatively new technology and no local capital costs could be found for South Africa, hence a method to estimate the capital cost was developed. The ratio between the capital cost for a pelleting plant and TOP plant was established, using literature-derived international costs. This ratio was then used to convert the South African cost for a pelleting plant, into an equivalent South African price for a TOP plant. Depending on the intended production capacity of the processing plant, the purchase prices will change accordingly. A relationship was determined between the capital cost and production capacity, using the above ratio-costing approach.

The ratio between the capital cost and the production capacity was determined by comparing the costs for a pelleting plant and a TOP plant, both reported as having the same production capacity (60 kt/yr). Table 4.6 contains the appropriate costs and the calculated ratio.

Table 4.6 Capital cost ratio: TOP plant (Uslu *et al.*, 2008; Nemeth, 2009; Nilsson *et al.*, 2011)

Production Capacity (kt/yr)	**Capital Cost (Euro × 10^6)**		**Ratio**
	Pelleting	**TOP**	
60	4.9	11	2.24

The capital cost for a TOP plant of varying production capacities can be calculated by modifying Equation 4.1 to get Equation 4.2, by using the ratio in Table 4.6. Equation 4.2 can be seen below.

$$P_{TOP} = (0.0489 y_{TOP} + 0.0972) * 2.24 \qquad (4.2)$$

where

P_{TOP} = purchase price [R × 10^6] for TOP plant, and

Y_{TOP} = plant production capacity [kt/h].

4.2.5.3 Torrefaction plant

The capital cost for a plant with a production capacity of 60 kt/yr was estimated as 6.5 million Euros by Uslu *et al.* (2008) and between 5.2 and 7.5 million Euros by Nemeth (2009). As with the pelleting and TOP plants, a South African capital cost for a torrefaction plant was required. The same method that was used to determine the capital costs for a TOP plant, was used to determine the capital costs for a torrefaction plant. The ratio between the capital cost for a pelleting plant and torrefaction plant was established, using literature-derived international costs. This ratio was then used to convert the South African cost for a pelleting plant, into an equivalent South African cost for a torrefaction plant. Depending on the intended production capacity of the processing plant, the purchase prices will change accordingly, and thus a regression was determined between the capital cost and production capacity, using the above ratio-costing approach.

The ratio between the capital cost and production capacity was determined by comparing the costs for a pelleting plant and a torrefaction plant, both reported for the same production capacity (60 kt/yr). Table 4.7 contains the appropriate costs and the calculated ratio.

Table 4.7 Capital cost ratio: torrefaction plant (Uslu *et al.*, 2008; Nemeth, 2009; Nilsson *et al.*, 2011)

Production Capacity (kt/yr)	**Capital Cost (Euro × 10^6)**		**Ratio**
	Pelleting	**Torrefaction**	
60	4.9	6.5	1.33

The capital cost for a torrefaction plant of varying production capacities can be calculated by modifying Equation 4.1 to get Equation 4.3, by using the ratio in Table 4.7. Equation 4.3 can be seen below.

$$P_{torr} = (0.0489 y_{torr} + 0.0972) * 1.33 \quad (4.3)$$

where

P_{torr} = purchase price [R], and

y_{torr} = plant output [kt/h].

4.3 Dynamics of Different Sheets

Each operation in the model was assigned a separate sheet within the Excel spreadsheet. The Chopper Harvesting, Manual Harvesting and Baling sheets all existed in the Economics of Trashing DSP. These existing sheets were modified to help make them more explicit and user-friendly. The five new sheets which were developed include Forage Harvesting, Silage Wagon, Torrefaction, Pelleting and TOP. This section contains details of each sheet, how it operates and how the different processes simulated in each sheet are computed. All of the sheets take into account loading and transport and thus, in order to prevent repetition, the loading and transport processes will be explained separately in Sections 4.3.10 and 4.3.11. A switch was added to each sheet, to determine whether a contractor was used for the transport of the sugarcane, residue or processed residue.

The aim of these sheets is to determine the number of machines used during the harvesting, loading and transport operations, as well as any costs incurred during these processes, such as for fuel and electricity. These values will then enable the model to calculate the cost for harvesting and collecting sugarcane/residue/processed residue, using the methods described in Section 4.2.

In each sheet, dropdown menus were put in place to help the user specify what piece of equipment was used for each process during the operation. Table 9.1 in Appendix A contains the choice of tractors, balers, forage harvesters, silage wagons, infield trailers, loaders, trucks and road trailers, which are available in these dropdown menus. Depending on which machinery is specified, the relevant costing data for that equipment will be brought forward and utilised. This costing data was explained fully in Section 4.2.

4.3.1 Chopper Harvesting sheet

The chopper harvesting sheet was included in the original version of EconoCane. The sheet originally considered the capital requirements for the chopper harvester, whether the harvester was harvesting burnt or green sugarcane, as well as the infield transport required for transporting the sugarcane. In an effort to make the sheet more realistic and user-friendly, additional elements were added, such as a switch to determine whether a contractor is used for sugarcane transport, an improved infield transport section, as well as a loading zone and road transport section.

This sheet receives general inputs from Table 9.2 and inputs specific to the chopper harvesting operation from Table 9.5, both of which can be found in Appendix A. The inputs in Table 9.5, such as the operating speed and average turn time, are used to calculate the total harvesting hours possible per harvester per day. Using this value and the potential harvesting rate of the harvester, the yield per day per harvester is computed. Depending on the area of sugarcane which needs to be cut per day and whether the sugarcane is green or burnt, this will influence the number of harvesters required. The harvesters will have to process a larger volume of biomass, if the sugarcane is green. The harvester speed infield will vary between 4.5 and 6.5 km/h, depending on whether burnt or green sugarcane is being harvested. If the sugarcane and residue are separated at the mill, it is assumed that 30% of the residue is left infield, as this residue falls off the sugarcane stalk before harvest (Weigel, 2009). The way in which the loading and transport requirements for the sugarcane are calculated, is explained in Sections 4.3.10 and 4.3.11.

The number of harvesters, loaders and transport vehicles, as well as the distance travelled and operating hours for each vehicle, all affect the cost per ton of harvesting the sugarcane. The distance travelled and operating hours for each vehicle, affect the fuel and tyre costs. The way in which the cost per ton is calculated for the harvesting operation has been explained in Section 4.2.

4.3.2 Manual Harvesting sheet

The manual harvesting sheet was included in the original version of EconoCane. The sheet includes all relevant processes which take place during harvesting, for example, whether the harvested sugarcane is burnt or green, whether it is placed in windrows, stacks or bundles after being cut, the number of cutters and foremen (indunas) required to harvest the sugarcane, the labour tools required, the management concession, as well the costs involved if a contractor was used to do the harvesting. Some inputs for this sheet come from the general inputs table found in Table 9.2, whilst the majority of the inputs and assumptions required for the modelling of the manual harvesting operation can be found in Table 9.3. Both these Tables are found in Appendix A.

This sheet was modified by adding user-selected options to simulate whether the sugarcane is specified as being placed in windrows, stacks or bundles. If the sugarcane is selected as being harvested green, the total mass of biomass that needs to be harvested is higher than that of burnt sugarcane, because of the added mass of the residue. This has an adverse effect on the harvesting cost. If the sugarcane is specified to be separated from the residue infield, the cost involved with this process is assumed to be double the cost of manually harvested burnt sugarcane (Norris, 2008). The transport and loading requirements are not included on the actual sheet, but are computed in a separate Transport sheet which has been linked to the Manual Harvesting sheet. This sheet uses the same methods that are described in Sections 4.3.10 and 4.3.11.

The number of loaders and transport vehicles, as well as the distance travelled and operating hours for each vehicle, will also affect the cost per ton of transporting the sugarcane. The distance travelled and operating hours for each vehicle, affect the fuel and tyre costs. The way in which the cost per ton is calculated for the transport operation is explained in Section 4.2. The harvesting cost is then added to the transport and loading costs, to find a total cost per ton for manually harvested sugarcane.

4.3.3 Residue recovery sheets

The sheets which relate to residue recovery all require information from a sheet called Losses, which already exists in EconoCane. This sheet is used to calculate the total residue yield in tons per hectare (wet basis). Inputs for this sheet include the percentage that sugarcane tops, leaves and stalks comprise of the total sugarcane plant mass. The percentage of recovered tops and leaves, which are lost during transportation, are also inputs. Before the tons of residue per hectare are computed, the total mass of fresh sugarcane residue per hectare is calculated. The mass of the sugarcane stalks per hectare is input and so is the percentage of the fresh mass that the stalks are comprised of. Using these values, plus the percentages that the tops and leaves comprise of the sugarcane plant mass, the total sugarcane biomass yield per hectare can therefore be calculated.

To calculate the percentage that the baled residue makes up of the total biomass, the fraction of tops is multiplied by the fraction of tops which are lost during transport, and this is added to the fraction of leaves multiplied by the fraction of leaves lost during transport. This gives the fraction of residue. This is then multiplied by the total mass per hectare of fresh sugarcane biomass, to determine the total residue yield in tons per hectare (wet basis).

The residue yield to be recovered per hectare (dry basis) is calculated by using the residue yield per hectare (wet basis), the initial moisture content of the residue and the residue mass per hectare, which is left infield for agronomic reasons. The initial moisture content of the residue is calculated by finding the average moisture content for the residue (tops and leaves). The quantity of residue left in the field for agronomic reasons was taken as 50% of the available residue (Brouckaert, 2014). The total residue (dry basis) is found using Equation 4.4.

$$T_b = T_f \times (1 - MC) \times (1 - T_{bl}) \quad (4.4)$$

where

T_b = residue recovered [t/ha],

T_f = fresh residue [t/ha],

MC = moisture content wet basis [%], and

T_{bl} = residue left infield i.e. residue blanket [%].

4.3.4 Baling

The baling sheet was included in the original version of EconoCane. The sheet included all relevant processes and did not require improvements. The operations which are included in this sheet are the tractor and rake operation, the tractor and baler operation, infield and zone loading operations, as well as infield and road transport. The loading and transport requirement calculations are explained in Sections 4.3.10 and 4.3.11.

The number of tractors, rakes and balers required is calculated by using input information, such as the area of sugarcane harvested per day, the operating speed, the machine efficiency and the field efficiency of each piece of equipment (Tables 9.2 and 9.4 in Appendix A). The field efficiency addresses the impact of time taken for turning, stopping and operational overlaps from one pass to the next as the machine goes through the field. The machine efficiency refers to the efficiency of the machine to do its designated job (i.e. rake material into a windrow or pick up material to bale). The speed at which a baler operates was taken as 4 km/h (Paul and Krishnamurthi, 2007; Lyne, 2014). Using these inputs, the work rate (ha/day) for each piece of equipment can be calculated. Using the total area of sugarcane harvested per day, the number of rakes and balers required can be calculated by dividing the total area by the work rate of a single rake or baler.

The number of tractors, rakes, balers, loaders and transport vehicles, as well as the distance travelled and operating hours for each vehicle, will influence the cost per ton of the residue recovery operation. The distance travelled and operating hours for each vehicle, affect the fuel, tyre and maintenance costs. The way in which the cost per ton is calculated for this operation was explained in Section 4.2.

4.3.5 Forage harvester

The forage harvesting sheet is a new sheet and it is similar to the Baling sheet. The only difference is that a forage harvester, instead of a baler, is used to collect the residue. The forage harvesters which were considered were trailed forage harvesters.

This sheet includes the costing for the use of a tractor and rake, a tractor and forage harvester, infield transport, loading at a zone, road transport and whether or not a contractor was used for the transport. The quantity of tractors, rakes and forage harvesters required for the residue recovery operation were calculated by using the same methods that were described in Section 4.3.4, with input values from Tables 9.2 and 9.7 (Appendix A). The way in which the loading and transport requirements for the sugarcane residue are calculated, is explained in Sections 4.3.10 and 4.3.11.

The number of tractors, rakes, forage harvesters, loaders and transport vehicles, as well as the distance travelled and the operating hours for each vehicle, will influence the cost per ton of the residue recovery operation. The distance travelled and operating hours for each vehicle affect the fuel, tyre and maintenance costs. The way in which the cost per ton is calculated for this operation was explained in Section 4.2.

4.3.6 Silage wagon

The Silage Wagon sheet is a new sheet which has been developed. It is based on the Baling sheet, with some minor changes. Infield transport is unnecessary, when using a silage wagon, and was thus not included in this sheet. The silage wagons which have been considered are trailed and they collect the residue in the wagon.

The processes which are included in this sheet are the tractor and rake operation, the silage wagon operation, loading at a zone, road transport and whether or not a contractor is used for transport. The number of tractors, rakes and silage wagons required for the residue recovery operation are calculated by using the same methods which were described in Section 4.3.4, with input values from Tables 9.2 and 9.6 (Appendix A). The way in which the loading and transport requirements for the sugarcane residue are calculated is explained in Sections 4.3.10 and 4.3.11.

The number of tractors, rakes, silage wagons, loaders and transport vehicles, as well as the distance travelled and operating hours for each vehicle, will influence the cost per ton of the residue recovery operation. The distance travelled and operating hours for each vehicle, affect the fuel, tyre and maintenance costs. The way in which the cost per ton is calculated for this operation has been explained in Section 4.2.

4.3.7 Torrefaction

This is a new sheet which has been developed. It takes into account three processes, namely, the torrefaction plant, loading at a loading zone and road transport of the processed material.

A torrefaction plant can be broken down into five main components, namely, the grinding unit, dryer, reactor, cyclones and conveyors (Zabaniotou and Karabelas, 1999). Each of these components of the torrefaction plant are included in the model, which is used to calculate the capital and maintenance costs for the plant. Although these components are included in the model, the plant can still be treated as an entity. Thus, if the price breakdown of the components of the plant is not available, the model will still operate, by taking the plant as a whole and not as separate entities. No literature was found, containing an accurate breakdown of the costs for each component of a torrefaction plant.

All inputs required for this sheet can be found in Table 9.2 (Appendix A). The total machine hours per year are calculated, using the operating days per year, the operating hours per day and the percentage downtime that can be expected per year. The operating days per year was set to 220 days (Smithers and Lyne, 2013), the operating hours per day was assumed to be 24 hours (Eksteen, 2013) and the percentage downtime per year was fixed at 6% (Svanberg *et al.*, 2013).

The capital cost for the varying sizes of torrefaction plants is required. The way in which the capital cost was found, has been described in Section 4.2.5.3. The transport and loading requirements for the processed residue are calculated, using the methods described in Sections 4.3.10 and 4.3.11. The percentage mass lost during the torrefaction process is an important value, as it will influence the loading and transport requirements. This percentage is assumed to be 30% (Wang *et al.*, 2013).

The capital cost of the torrefaction plant, the number of loaders and transport vehicles, as well as the distance travelled and operating hours for each vehicle, will influence the cost per ton of the residue processing operation. The distance travelled and operating hours for each vehicle affect the fuel and tyre costs, whilst the operating hours for the torrefaction plant will influence its electricity cost. The way in which the cost per ton is calculated for this residue processing operation has been explained in Section 4.2.

4.3.8 Pelleting

This sheet followed the same principle as the torrefaction sheet. It takes into account the operation of the pelleting plant, the loading at a loading zone and the road transport of the processed material.

A pelleting plant can be broken down into nine main components. These include the grinding unit, the dryer, hammer mill, feeder and boiler, the pellet mill, the cooler, as well as bagging and conveying (Sultana *et al.*, 2010; Nilsson *et al.*, 2011). The percentage of the total capital cost of the plant for each of these components is summarised in Table 4.8. These percentages will be used to determine the breakdown of costs involved with the purchase and maintenance of the plant.

As with the torrefaction sheet, all inputs required for the pelleting sheet can be found in Table 9.2 (Appendix A). The total machine hours per year was calculated in the same way as described in Section 4.3.7, with the same assumptions regarding operating days per year, operating hours per day and percentage downtime per year.

As with the torrefaction sheet, estimating the capital cost of a pelleting plant for different input capacities is required. Section 4.2.5 describes the methods used to determine the capital costs involved. The loading and transport requirements for the processed residue are calculated by using the methods described in Sections 4.3.10 and 4.3.11.

Table 4.8 Pelleting cost breakdown (Sultana *et al.*, 2010)

Component - Process	Fraction of Purchase Price (%)
Grinder	26.8
Dryer	17.7
Hammer mill	6.2
Feeder and boiler	3.9
Pellet Mill	15.2
Cooler	7.0
Bagging and conveying	23.2

The capital cost of the pelleting plant, the number of loaders and transport vehicles, as well as the distance travelled and operating hours for each vehicle, will influence the cost per ton of the residue processing operation. The distance travelled and operating hours for each vehicle, affect the fuel and tyre costs, whilst the operating hours for the pelleting plant will influence its electricity cost. The way in which the cost per ton is calculated for this residue processing operation, has been explained in Section 4.2.

4.3.9 TOP

This sheet followed the same principle as the torrefaction sheet. It takes into account the operation of the TOP plant, the loading at a loading zone and the road transport of the processed material.

A TOP plant can be broken down into eleven main components. These include infrastructure, tipping bunkers and processing, driers, the reactor, a steam boiler, cooling and milling, pelleting and cooling, as well as discharge and outdoor storage (Svanberg *et al.*, 2013). The percentage of the total capital cost of the plant, of which each of these components is comprised, is summarised in Table 4.9. These are used to determine the breakdown of costs involved with the purchase and maintenance of a TOP plant.

As with the torrefaction sheet, all inputs required for the TOP sheet can be found in Table 9.2 (Appendix A). The total machine hours per year were calculated in the same way as described in Section 4.3.7, with the same assumptions regarding operating days per year, operating hours per day and percentage downtime per year.

As with the torrefaction and pelleting sheets, estimating the capital cost of a TOP plant for different input capacities is required. Section 4.2.5.2 describes the methods used to determine the capital costs involved. The transport and loading requirements for the processed residue are calculated by using the methods described in Sections 4.3.10 and 4.3.11. As with a torrefaction plant, the percentage mass lost during the TOP process is an important value, as it will influence the loading and transport requirements. This percentage is taken as 30% (Wang *et al.*, 2013).

Table 4.9 TOP cost breakdown (Svanberg *et al.*, 2013)

Component - Process	% Purchase Price
Infrastructure	13.1
Tipping bunkers, fuel processing	14.4
Driers	14.7
Reactor	15.3
Boiler	24.4
Cooling	2.5
Milling	1.6
Pelleting and cooling	14.0

The capital cost of the TOP plant, the number of loaders and transport vehicles, as well as the distance travelled and operating hours for each vehicle, will influence the cost per ton of the residue processing operation. The distance travelled and operating hours for each vehicle affect the fuel and tyre costs, whilst the operating hours for the TOP plant will influence its electricity cost. The way in which the cost per ton is calculated for this residue processing operation has been explained in Section 4.2.

4.3.10 Loading

Inputs specific to loading can be found in Tables 9.2 and 9.8 (Appendix A). The number of infield and zone loaders required is calculated by using the total tons of sugarcane/residue/processed residue to be loaded per day, the loading rate of the loaders and the operational hours of the loaders per day. The mass of sugarcane/residue/processed residue to be loaded per day per loader is found by using the loading rate and the working hours of the loaders. In order to calculate the total number of loaders required, the total tons of sugarcane/residue/processed residue to be loaded per day is divided by the mass of sugarcane/residue/processed residue loaded per loader per day.

The loaders which will be used for infield loading and transloading, can be specified from the dropdown menus. The loading rate of the loading operation will depend on the loaders selected and whether the sugarcane is green or burnt, unless the user specifies a loading rate. When loading green sugarcane with residue, the loading rate decreases by 23%. Table 4.10 contains the loaders available for selection and their respective loading rates.

Table 4.10 Loaders and their respective loading rates (Tweddle, 2013)

Loader	Loading rate (t/h)
Bell: 125 (3)	20
Bell: 125 (4)	20
Bell: 220 (4)	25
Slew: Sml	25
Slew: JD1850	25
Slew: JD2254	30

4.3.11 Transport

Inputs specific to this operation can be found in Tables 9.2 and 9.8 (Appendix A). The distance from the field to the mill, as well as the infield tractor/trailer combination, will determine whether road transport, and hence a loading zone, will be required. The user can select the tractor/trailer combination that will be used for infield transport from a dropdown menu. Table 9.1 contains the available selection of tractors, whilst Table 4.11 contains the available selection of infield trailers, with the maximum distance from the field that these trailers should be allowed to travel (unless the user specifies the distance). For the silage wagon operation, where no separate infield transport is required, the silage wagon can travel a maximum of 5 km, before road transport becomes necessary (Domleo, 2013). The distance that the road transport will have to travel will be the maximum distance that the infield trailer/silage wagon will travel, subtracted from the distance between the field and the mill.

The number of vehicles required for infield and road transport, is calculated using the expected yield per day of sugarcane/residue/processed residue, the density of the sugarcane/residue/processed residue, as well as the maximum load and capacity of the trailers used. The densities of the materials to be transported in the different sheets are summarised in Table 4.13, with the volume and capacities of the infield trailers summarised in Table 4.11 and the volume and capacities of the road trailers summarised in Table 4.12. The volume of any road trailer is assumed to be 105 m^3, unless the user specifies otherwise.

Table 4.11 Infield trailer characteristics (Lubbe *et al.*, 2013; Landmech, 2014; Lyne, 2014; Unicab, 2014)

Trailer	Maximum Distance (km)	Volume (m^3)	Maximum Load (t)
Ag: 1 basket	0.5	15	8
Ag: 1 side SLT	0.5	15	8
Ag: Dbl box	0.5	15	8
Ag: Dbl side SLT	0.5	15	8
Ag: 6T Tip	0.5	12	6
Ag: 10T Tip	0.5	20	10
H: 15T Spiller	5.0	53	15
H: 2x14T Spiller	10.0	106	28

Table 4.12 Road trailer characteristics (Lubbe *et al.*, 2013; Tweddle, 2014)

Trailer	Volume (m^3)	Maximum Load (t)
22t T/tr spiller	105	22
30t T/tr spiller	105	30
34t T/tr spiller	105	34
34t R&Db spiller	105	34

Payload is an important factor in transport economics. The density of the sugarcane will depend on how it has been harvested and packed into transport vehicles, whilst the density of the residue will depend on how it is collected, and if/how it is processed. Green sugarcane with residue intact has a lower bulk density and thus the average payload for green sugarcane is reduced (Paul and Krishnamurthi, 2007). The densities will have an effect on the transport requirements and costs, as they will determine the maximum payloads which can be transported. Specialist input is often required when updating variables in this sheet. It was assumed that burnt whole-stick sugarcane has the same density as clean green sugarcane.

The expected cycle time for each transport vehicle can be calculated by using the speed at which the vehicle travels, the distance travelled and the rate at which it can be loaded and unloaded. The speed of infield and road transport is an input value, but the default values are 10 km/h and 60 km/h, respectively (de Lange, 2014). The operating hours per day are obtained from the input sheet (Table 9.2) and, using the cycle time, it is possible to calculate how many tons of sugarcane/residue/processed residue each vehicle can transport in one day.

Using the total tons to be transported per day, the number of required vehicles can be calculated.

Table 4.13 Densities of transported material (Hassuani *et al.*, 2005; Uslu *et al.*, 2008; Pottinger, 2013; Smithers and Lyne, 2013)

Material	Bulk Density (kg/m^3)
Sugarcane (wet basis)	
Whole-stick: clean/burnt sugarcane	320
Whole-stick: sugarcane with residue intact	240
Billeted: clean/burnt sugarcane	350
Billeted: sugarcane with residue (no separation)	250
Billeted: sugarcane with residue (partial separation)	280
Residue (dry basis)	
Baler	
Round: small	118
Round: large	95
Rectangular	175
Forage harvester	70
Silage wagon	140
Processed residue (dry basis)	
Torrefaction	300
Pelleting	575
TOP	800

4.4 Sugarcane Harvesting and Residue Recovery Cost Calculations

It was assumed that a sugar milling company will only be willing to pay a coal equivalent price for sugarcane residue and thus, the cost per unit energy to harvest green sugarcane and recover the residue (R/GJ), should be less than that of coal (R/GJ), in order for it to be an economically-feasible fuel source. The methods used to calculate the cost per unit energy for sugarcane residue and coal, are described in this section.

If residue recovery is employed, the subsequent presence of a residue blanket will cause a reduction in both electricity consumption for irrigation and herbicide requirements. This agronomic benefit is quantified, using the equations described below.

4.4.1 Sugarcane residue recovery cost (R/t residue)

Sugarcane residue recovery requires the implementation of green sugarcane harvesting. There is a difference in cost, termed the green sugarcane harvesting cost deficit, between harvesting burnt and green sugarcane. This is the first cost incurred when sugarcane residue recovery is employed. The residue is then either separated at the mill, or separated infield. If the residue is separated at the mill, the green sugarcane harvesting cost deficit and the cost of dry residue separation will be considered, as the dry residue is transported to the mill with the sugarcane. The cost of dry residue separation at the mill was taken as R 7.60 per ton of sugarcane harvested in the year 2008 (Norris, 2008). This cost includes the capital and maintenance costs for the whole-stick sugarcane billeting and separation equipment. Using an inflation rate of 6% (Fedec and Sousa, 2014), this value was inflated to a present day value of R 10.78 per ton of harvested sugarcane. Equation 4.5 is used to find the cost per ton of dry residue recovery at the mill (C_{rmill}).

$$C_{rmill} = \frac{(10.78 + (C_{gh} - C_{bh})) \times T_s}{T_r} \quad (4.5)$$

where

C_{rmill} = cost of residue recovery [R/t residue],

C_{gh} = cost to harvest and transport green sugarcane [R/t sugarcane],

C_{bh} = cost to harvest and transport burnt sugarcane [R/t sugarcane],

T_s = tons of sugarcane harvested [t], and

T_r = tons of dry residue collected [t].

If the residue is separated infield (the residue is not dry residue) the cost of residue separation (C_s) comprises three elements, namely, the harvesting cost deficit, the residue recovery operation cost and the residue processing operation cost. The Economics of Trashing DSP gives an output cost per ton for each of these. The cost per ton is specific to sugarcane residue, for the sugarcane residue recovery operation, and specific to processed residue, for the sugarcane residue processing operation. For this reason, these costs cannot be added together, to get a total cost per ton. Therefore, if the residue is separated infield, the total cost for this operation can be found, using Equation 4.6.

$$C_{rfield} = \frac{(C_r \times T_r) + (C_p \times T_p) + ((C_{gh} - C_{bh}) \times T_s)}{T_r} \quad (4.6)$$

where

C_{rfield} = cost of residue recovery [R/t residue],

C_p = cost of residue processing [R/t processed residue], and

T_p = tons of processed sugarcane residue [t].

The cost of residue recovery infield (C_{rfield}) includes the relevant loading and transport costs involved with the residue recovery and processing, whilst the cost of residue recovery at the mill (C_{rmill}) does not include these, as the residue arrives at the mill with the sugarcane. The total tons of sugarcane collected (T_s) will vary, depending on whether the residue is separated infield or at the mill, and this value will have an effect on the cost of residue separation (C_{rmill} or C_{rfield}). If the residue is separated infield, it was assumed that approximately 50% (Brouckaert, 2014) of the residue is left infield for agronomic reasons and of the 50% left for collection, approximately 70% (Hassuani *et al.*, 2005) of that is collected because of the collection efficiency of the recovery machinery. Thus, approximately 35% of the available residue gets delivered to the mill, if the residue is separated infield. If there is no infield separation i.e. the residue is separated at the mill, approximately 70% of the available residue is delivered to the mill. The reason for this is that approximately 30% of the residue on the sugarcane stalks fall to the ground before and during the harvest operation (Weigel, 2009). If there is partial separation infield i.e. the residue is separated at the mill, approximately 35% of the available residue is delivered to the mill. Another aspect to consider is that when residue is separated at the mill, it will not include any sugarcane tops; however, when residue is separated infield, there is a high chance that there will be sugarcane tops in the residue. This is a problem which needs to be addressed by future residue recovery machinery developers.

4.4.2 Cost per unit energy (R/GJ)

To make an economic comparison between sugarcane residue and coal as a potential source of energy, a common unit is required for the comparison. This common unit is cost per unit energy (R/GJ). To find the cost per unit energy for sugarcane residue, the cost of residue separation (R/t) and the energy density of the residue (GJ/t) is required, as seen in Equation 4.7. The energy density of the sugarcane residue, taken from Table 4.14, was assumed to be 16.7 GJ/t.

$$C_{er} = \frac{C_r}{ED_r} \tag{4.7}$$

where

C_{er} = cost per unit energy of sugarcane residue [R/GJ],

C_r = cost of residue extraction, separation and delivery to the mill [R/t residue], and

ED_r = energy density of residue [GJ/t].

The cost per unit energy for coal is found using the current cost of coal at a sugar mill and the energy density of coal, as detailed in Equation 4.8. The current coal cost was taken as R 1060 per ton (de Lange, 2014) and the energy density of coal was taken as 29.3 GJ/t (Society, 2014).

$$C_{ec} = \frac{C_c}{ED_c} \qquad (4.8)$$

where

C_{ec} = cost per unit energy of coal [R/GJ],

C_c = cost of coal [R/t], and

ED_c = energy density of coal [GJ/t].

The cost per unit energy (C_{ec}) was found to be 36.18 R/GJ. Therefore, if C_{er} is less than this value, sugarcane residue can be seen as an economically-viable fuel source. If it is not, then there is no economic benefit to utilising sugarcane residue for that harvested area.

4.4.3 Agronomic benefit (R/t residue)

The presence of a residue blanket after harvesting can result in an agronomic benefit for the grower. This agronomic benefit is economically quantified using Equation 4.9 and consists of two major elements, namely, the reduced electricity requirement for irrigation and the reduced herbicide demand for the field after harvest (Wynne and van Antwerpen, 2004; van Antwerpen *et al.*, 2008). An additional agronomic benefit is the increase in yield of approximately 9 t/ha/yr, if the blanket consists of residue, and approximately 6.3 t/ha/yr, if the blanket consists of green residue (Thompson, 1966; van Antwerpen *et al.*, 2006). These increases in yield can be attributed to a reduction in soil evaporation of 90 mm/ha/yr and 63 mm/ha/yr, respectively (Thompson, 1966). If the model is run for a number of consecutive years, these increases in yield will be taken into account. The reduced electricity requirement for irrigation will depend on whether the harvested area was originally under irrigation or not. Approximately 70% of the South African sugar industry is rainfed, with the remainder being irrigated (van Antwerpen *et al.*, 2006). There will therefore be no cost reduction in the irrigation requirement if the modelled area is rainfed.

$$AB = \frac{A(I_r + H_r)}{T_r} \qquad (4.9)$$

where

AB = agronomic benefit [R/t residue],

A = area harvested [ha],

I_r = reduction is electricity requirement for irrigation [R/ha], and

H_r = reduction in herbicide requirement after harvesting [R/ha].

AB will give the grower an indication of the potential saving, if green sugarcane harvesting were to be implemented. These aforementioned calculations for the sugarcane residue recovery cost, cost per unit energy and agronomic benefit, are used in Chapter 0, where the model is applied to a number of case studies.

4.5 Energy Calculations

The recovery of sugarcane residue from the field would not be feasible if the energy required to recover and process the sugarcane residue outweighed the amount of energy available in the residue. The energy savings that come with a residue blanket also needs to be taken into account. This is illustrated in Equation 4.10.

$$E_{potential} + E_{savings} = E_{expended} \qquad (4.10)$$

where

$E_{potential}$ = potential energy available in sugarcane residue [GJ],

$E_{savings}$ = energy saved by residue blanket [GJ], and

$E_{expended}$ = energy expended during recovery and processing [GJ].

The amount of energy available in the collected residue is calculated by multiplying the mass of the collected residue by the energy density of the residue, as seen in Equation 4.11. The mass of the residue and its energy density, will depend on whether the residue was processed or not. Table 4.14 contains the energy densities of residue in different forms.

$$E_{available} = T_r \times E_{dr} \qquad (4.11)$$

where

E_{dr} = energy density of residue [GJ/t].

The residue blanket will cause a reduction in evapotranspiration, a reduced in irrigation water requirement and thus a reduction in the energy requirement for irrigation. This energy saving requires the electricity deficit and electricity energy density as inputs, as shown in Equation

4.12. The energy deficit is calculated by subtracting the energy requirement for burnt sugarcane from the energy requirement for green sugarcane i.e. residue blanket present. The energy density of electricity is found in Table 4.14.

$$E_{savings} = I_{eu} \times E_{de} \qquad (4.12)$$

where

I_{eu} = irrigation electricity usage deficit [kWh/ha/yr], and

Ede = energy density of electricity [GJ/kWh].

The direct energy required for the residue recovery and processing operation will be determined using Equation 4.13 and will include fuel and electricity usage. The required energy densities are summarised in Table 4.14. The electricity and fuel costs contained in Section 4.2.1 are used in this calculation.

$$E_{used} = \left(\frac{F_e}{R_f} \times E_{dd}\right) + \left(\frac{E_e}{R_e} \times E_{de}\right) \qquad (4.13)$$

where

F_e = fuel expenditure [R],

E_e = electricity expenditure [R],

R_f = fuel price [R/l],

R_e = electricity price [R/kWh], and

E_{dd} = energy density of diesel [GJ/l].

Table 4.14 Energy densities

	Energy Density	**Units**	**Reference**
Loose residue	16.7	GJ/t	(Prabhakar *et al.*, 2010)
Torrefied residue	20.4	GJ/t	(Uslu *et al.*, 2008)
Pelleted residue	17.7	GJ/t	(Uslu *et al.*, 2008)
TOP residue	22.7	GJ/t	(Uslu *et al.*, 2008)
Electricity	0.0036	GJ/kWh	(Eskom, 2014)
Diesel	0.036	GJ/l	(Shell, 2014)

These calculations are used in Chapter 0.

5. MODEL VALIDATION

The model needed to be validated to ensure that it was giving reasonable cost estimates. Data from actual field trials would ideally help ensure the validity of the model outputs; however, sugarcane residue processing has not yet been implemented commercially in South Africa, and most of the residue recovery trial results conducted in South Africa are confidential.

The following options were considered to validate the model: (i) Sugarcane residue baling data from trials conducted in the Noodsberg Mill area, (ii) Mr. A Senekal, who is constructing a biomass energy plant in Mkuze, KZN, with the aim of recovering sugarcane residue, (iii) residue recovery field trial data from Tongaat Hulett (THS), (iv) Mr. C Norris, head of Norris Energy Crop Technology, who has vast experience in the recovery and use of sugarcane residue, and (v) trials conducted by the Mpumalanga Cane Growers Association, for utilising sugarcane residue recovery and residue processing (Murray *et al.*, 2013).

Baling trial data was obtained from the Noodsberg Mill, and this was used to validate a section of the model. The other options were not successful, as the required data could either not be obtained, or the data was not made available within a reasonable period of time.

5.1 Noodsberg Mill Area: Baling Trial Inputs

Sugarcane residue baling trials were conducted in 2008 in the Noodsberg Mill area. The operation involved the sugarcane being harvested using a chopper harvester, and the residue being left in the field to dry for approximately three days. The residue was then baled and transported to the mill. The mill paid the grower for the sugarcane residue in terms of the equivalent energy cost of coal at the time (de Lange, 2014). This value was approximately R 300/t. The trial results are summarised in Table 5.3. The Economics of Trashing DSP was run with inputs specific to the Noodsberg Mill area (Table 9.2 in Appendix A), with the objective of comparing the model output to the costs incurred during the trial. Other inputs specific to the trial, and which had to be incorporated into the model, are summarised in Table 5.1. Care was taken to ensure that correct discounted values specific to the year (2008) and relative costs specific to 2008 were used. With regards to the machinery used in the baling trial, the model was set up to most closely resemble the machinery which was used in the trial. There is a wide range of machinery available in the model database, as described in Section 4.2; however, the database did not contain the exact machinery used in this baling trial. For this reason the tractors in Table 5.2 are not exactly the same as the tractors which were used in the trial (Table 5.1).

Table 5.1 Noodsberg Mill area: Input values for baling trial conducted in 2008

Input	Item/Value	Reference
Baler	Claas Baler 350	(de Lange, 2014)
Rake	Claas Liner	(de Lange, 2014)
Tractor (baling)	Claas 456 4x4 72 kW	(de Lange, 2014)
Tractor (raking)	Claas 446 4x4 66 kW	(de Lange, 2014)
Diesel price	R 10.00/litre	(de Lange, 2014)
Interest rate	11%	(Triami Media, 2014)
Residue yield	20 t/ha	(de Lange, 2014)

Table 5.2 Noodsberg Mill area: Model input values for trial conducted in 2008

	Machinery			
	Baler	**Rake**	**Tractor 60 kW FWA (raking)**	**Tractor 75 kW FWA (baling)**
Operating speed (km/h)	4	6	6	4
Machine efficiency (%)	70	90	90	70
Purchase price (R)	279 000	60 000	270 000	300 000
Operator (R)	0	0	32 500	32 500
Licence and insurance (R)	2 790	100	2 700	3 000
Life (h)	2250	2000	10000	10000
Tyres:-				
Price (R)	3 000	0	23 800	24 000
Life (h)	3000	0	3000	3000
Fuel :-				
Consumption (l/h)	0	0	6	7
Maintenance:				
% Price	130	60	100	100
Max. life (yr)	5	15	15	15
Resale :-				
Base %	10	35	40	40
Base age (yr)	2	5	5	5
Yearly %	10	5	2	2
Minimum price (%)	10	10	12	12

5.2 Noodsberg Mill Area: Baling Trial Results and Model Validation

The simulation of the baling trial results summarised in Table 5.3 include the term 'harvesting cost deficit'. The harvesting cost deficit (as described in Section 4.4.1) is the additional cost involved by harvesting green sugarcane rather than burnt sugarcane. This value is found by subtracting the cost for harvesting burnt sugarcane with a chopper harvester, from the cost of harvesting green sugarcane with a chopper harvester (separation fans on). The input values from Table 9.2, Table 5.1 and Table 5.2 were used in the model and the output costs are summarised in Table 5.4.

Table 5.3 Noodsberg Mill area: Trial results (de Lange, 2013)

Operation	Cost	
Harvesting cost deficit	R 7.15	per ton sugarcane
Rake + tractor	R 59.60	per ton residue
Baler + tractor	R 153.88	per ton residue
Twine	R 12.00	per ton residue

Table 5.4 Noodsberg Mill area: Model results

Operation	Cost	
Harvesting (chopper harvester, green sugarcane, separation)	R 33.51	per ton sugarcane
Harvesting (chopper harvester, burnt sugarcane)	R 27.22	per ton sugarcane
Harvesting cost deficit	R 6.29	per ton sugarcane
Rake + tractor	R 37.61	per ton residue
Baler + tractor	R 156.89	per ton residue
Twine	R 12.00	per ton residue

The harvesting cost deficit is similar for both the baling trial results and the model results, which shows that the model is able to take into account the differences between harvesting burnt and green sugarcane. The raking operation cost for the baling trial was R 21.99/t of residue more than the cost for the same operation in the model. This difference could be attributed to a lower-than-expected work rate or field efficiency during the baling trial. The baling operation costs are very similar for the baling trial and the model, and this therefore suggests that the model can be relied upon for accurate baling estimates for this mill area. The twine input cost which was used in the model, was taken from this trial, and thus the model output twine cost will be the same as the trial.

6. CASE STUDIES

To assess the model and to compare the cost of different residue recovery routes, the model was run for two different sugarcane producing areas. This helped determine the least-cost residue recovery route for each area, based on the assumptions made. All assumptions were hypothetical, relevant to June 2014 and specific to each scenario. The two case studies include: (i) a mill supply area in the KwaZulu-Natal Midlands (Noodsberg), and (ii) a hypothetical large-scale grower who is hauling over long distance. The model results are summarised in this chapter.

6.1 Noodsberg Mill Area

The model was run for the Noodsberg Mill area in order to obtain a present-day comparison for the different residue recovery routes available. Unlike the model validation, the model was run to find present-day costs and thus the interest rate, fuel price and machinery purchase prices have been changed accordingly, to present-day values. A flowchart of the costs involved with each residue recovery route can be found in Figure 6.1. The agronomic benefit of each route has been included in Figure 6.1; however, it does not form part of the residue recovery cost. Residue recovery routes can be separated into the three elements of sugarcane harvesting, residue recovery and residue processing. Each of these elements and their respective costs are summarised in Figure 6.1. Refer to Tables 12.1, 12.2 and 12.3 in Appendix D for a more detailed breakdown of these costs. Two methods of harvesting are considered in Figure 6.1, namely, manual harvesting (stack) and chopper harvesting. The other two forms of manual harvesting (windrow and bundle) were not considered, as the cost difference, between the three methods of manual harvesting, to harvest the sugarcane and transport it 25 km, is insignificant, as evident from the results in Table 6.1. The machinery used for each recovery route is listed in Table 6.2. In order to ensure a fair comparison between the recovery routes, the machinery utilised for the transport and loading operations remained the same, regardless of the residue recovery route.

Table 6.1 Noodsberg Mill area: Manual harvesting method cost comparison

Manual Harvesting Method	Cost (R/t)	
	Burnt Sugarcane	Green Sugarcane
Stack	R 70.20	R 85.49
Windrow	R 69.99	R 85.16
Bundle	R 69.99	R 85.16

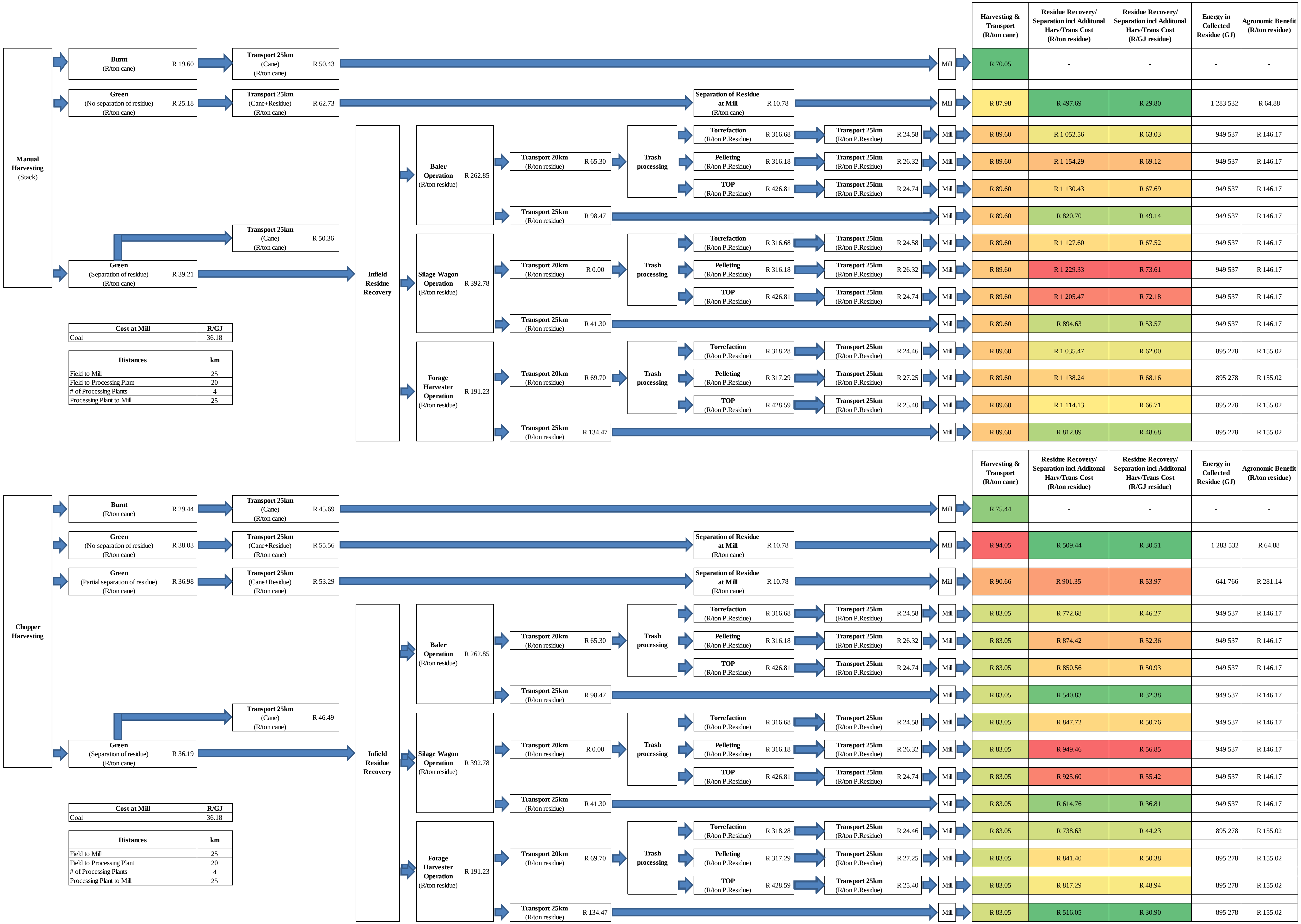

Figure 6.1 Noodsberg Mill area: Residue recovery route cost flowchart

Table 6.2 Noodsberg Mill area: Machinery utilised

Operation	Type of Machinery	Detail
Residue recovery		
	Tractor (raking)	Ag: 60kW-FWA
	Tractor (baler/FH/SW)	Ag: 75kW-FWA
	Baler	RB: 1.2m
	Forage harvester (FH)	Trailed 2.2m
	Silage wagon (SW)	17 cubic m
Infield transport		
	Tractor	Ag: 55kw-FWA
	Trailer	Ag: Dbl box
Loading		
	Loader (infield)	Bell: 125(3)
	Loader (transloading zone)	Bell: 125(3)
Road transport		
	Truck	14t
	Trailer	30t T/tr spiller

6.1.1 Optimum size of processing plant

An investigation was conducted to determine the optimum size and number of plants required to satisfy the residue processing requirements for the Noodsberg Mill area. This was done to ensure that the model's residue processing cost outputs were best-suited to the Noodsberg Mill area. The optimum plant size would therefore be the least-cost solution. In an effort to avoid over-complication, it was assumed that all available residue was processed, when residue processing was implemented. The average field-to-mill distance is 25 km for the Noodsberg Mill area, whilst the annual area harvested is 15 860 ha (de Lange, 2014). It was assumed that the supply area to the mill was circular and could fit within a circular band one kilometre wide, at a radius of 25 km from the mill, as depicted in Figure 6.2. The required capacity of a processing plant is relative to the area which supplies the plant. Thus, in order to determine the optimum plant size, the radius of the area supplying a plant was varied from one km and was increased incrementally to 120 km. To determine the number of processing plants required for each corresponding plant size, the circumference of the band of the harvested area (radius 25 km) was divided by the distance between proposed plants (diameter of plant supply area). This method is demonstrated in the bottom-right corner of Figure 6.2. Table 6.3 displays the results from the investigation and includes the cost to collect and haul the sugarcane residue to the processing plants, using a forage harvester, followed by residue processing by TOP, which is then transported to the mill. This residue recovery route was chosen, as it was proved to be the least-cost recovery route when no residue processing is implemented. The plant capacity which has the least-cost is thus the optimum plant size for the mill area.

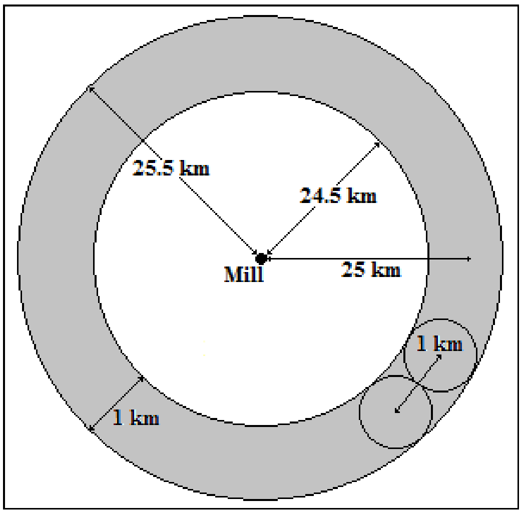

Figure 6.2 Diagram depicting optimum size processing plant calculations

The results displayed in yellow in Table 6.3, suggest that a supply area radius of 40 km would be the best-suited option for the Noodsberg Mill area; however, the average field-to-mill distance is 25 km and thus distances greater than 25 km to the processing plant were not considered. For supply area radii of 25 km, or less, a radius of 20 km was the least-cost option, as highlighted in green in Table 6.3. Thus, when residue processing was selected in a recovery route in Figure 6.1, it was assumed the residue was transported an average of 20 km to a processing plant, where it was processed and then transported 25 km to the mill. Table 6.3 shows that four processing plants are required for a processing plant radius of 20 km.

Table 6.3 Noodsberg Mill area: Optimum size and quantity of processing plants

Forage Harvester – TOP			
Distance to Mill (km)	**Supply Area Radius (km)**	**Plants Required**	**Operation Cost**
25	1	79	R 331 757 441
25	2	40	R 175 153 640
25	3	27	R 123 090 811
25	4	20	R 95 151 286
25	5	16	R 79 274 885
25	10	8	R 48 143 013
25	15	6	R 40 890 403
25	20	4	R 33 551 268
25	25	4	R 34 496 939
25	30	3	R 31 176 476
25	35	3	R 31 879 296
25	40	2	R 28 805 597
25	50	2	R 30 447 119
25	70	2	R 33 741 957
25	80	1	R 31 103 942
25	120	1	R 37 683 431

6.1.2 Output costs discussion

The following discussion concerns sugarcane residue recovery operations in the Noodsberg Mill area and refers to Figure 6.1 and Table 6.4. The mill currently pays R 36.18/GJ for coal (June 2014), and is willing to pay the equivalent price for sugarcane residue (de Lange, 2014). This equates to approximately R 600/t, which the mill is willing to pay for sugarcane residue. If the sugarcane grower can recover sugarcane residue for less than that, then there is a profit to be made and sugarcane residue recovery is economically feasible.

The recovery routes presented in Table 6.4, which have a cost that is highlighted in green, are the routes which cost less than the coal equivalent cost. The least-cost residue recovery route occurs when the sugarcane is manually-harvested and the residue is separated at the mill (R 29.80/GJ). International studies conducted in Cuba (Alonso-Pippo *et al.*, 2008), Australia (Thorburn *et al.*, 2007) and Brazil (Marchi *et al.*, 2005) found that the least-cost residue recovery route occurs when the sugarcane is harvested, using a chopper harvester, and the residue is separated from the sugarcane at the mill. This shows that for the Noodsberg Mill area, manual harvesting may be the least-cost harvesting method; however, the model does concur with the international studies, as it suggests that residue separation at the mill is the least-cost residue recovery method. The reason for the difference in cost between the manually harvested and the chopper harvester routes, where residue separation occurs at the mill, is the harvesting cost difference between these harvesting methods (R 87.98/t versus R 94.05/t of sugarcane).

Table 6.4 Noodsberg Mill area: Summary of least-cost residue recovery routes

Least-cost Residue Recovery Routes					Total Cost (R/GJ)
Rank	**Harvesting Method**	**Separation (Field/Mill)**	**Recovery Machinery**	**Residue Processing**	
1	Man	Mill	-	-	R 29.80
2	CH_{ffo}	Mill	-	-	R 30.51
3	CH_{ffo}	Field	Forage Harvester	-	R 30.90
4	CH_{ffo}	Field	Baler	-	R 32.38
5	CH_{ffo}	Field	Silage Wagon	-	R 36.81
6	CH_{ffo}	Field	Forage Harvester	Torrefaction	R 44.23
7	Man	Field	Forage Harvester	-	R 48.68
8	Man	Field	Baler	-	R 49.14
9	Man	Field	Silage Wagon	-	R 53.57
10	Man	Field	Forage Harvester	Torrefaction	R 62.00
where: Man = Manual Harvesting (Stack)					
CH_{ffo} = Chopper Harvester (fans fully on)					

Table 6.4 also shows that, if the residue is separated infield, the least-cost residue recovery route would be to mechanically harvest the sugarcane, followed by residue collection, using a forage harvester. A baler, and then a silage wagon, are the next least-cost infield residue recovery options. The reason for the difference in cost between the manually-harvested and the chopper harvester routes, where residue separation occurs infield, is the harvesting cost difference between these harvesting methods (R 89.60/t versus R 83.05/t of sugarcane).

As seen in Figure 6.1 and Table 6.4, and based on the assumptions made, the cost of processing residue is not economical for the Noodsberg Mill area. The least-cost processing option is R 44.23/GJ, which is approximately R 14 more per GJ than if separation had to occur at the mill. It is also approximately R 8 more per GJ than the cost of coal. It is for these reasons that residue processing should not be considered for the Noodsberg Mill area, as it is not the least-cost recovery route available and is not economically feasible.

It is important to note that an additional 50% of residue is collected, when residue is separated at the mill, compared to infield residue recovery. When the residue is separated at the mill, approximately 1 300 000 GJ of residue is collected, whilst only 900 000 GJ of residue is collected when separation occurs infield. This is an additional reason why it is best to separate residue at the mill. The residue which is collected when separation occurs at the mill, will only contain leaves; however, the residue which is separated and collected infield, will contain some sugarcane tops. Sugarcane tops are undesirable at the mill, which is why residue separation at the mill is beneficial, with regard to residue composition.

6.1.3 Overall cost and energy balance

It is desirable to determine whether sugarcane residue recovery is beneficial for the Noodsberg Mill area, with regards to both the overall effective cost and energy balance. These balances only consider the direct input costs and not the full life cycle cost. Therefore, only simplistic balances are produced, however, these do serve the function of giving an indication of whether residue recovery may be financially viable. These balances were both determined for the least-cost sugarcane residue recovery route. The residue recovery route involved manually harvesting green sugarcane and separating residue at the mill. It was assumed that the grower would receive a coal equivalent cost for the residue (R 600/ton). There will be no saving in electricity for irrigation, as the Noodsberg Mill supply area is rainfed. The results from this investigation are summarised in Table 6.5.

Table 6.5 Noodsberg Mill area: Cost feasibility of chosen residue recovery route

	Cost of Operation
Burnt sugarcane harvesting	
Manual (stack)	R 93 323 072.06
Green sugarcane harvesting	
Manual harvesting (stacks)	R 117 212 773.86
Separation at mill	R 14 361 547.20
Residue value	- R 46 114 921.01
Irrigation saving	R 0.00
Herbicide saving	- R 4 020 417.74
Total	R 81 438 982.31
Saving/Loss	+ R 11 884 089.75

The results in Table 6.5 suggest that it is more economically feasible to harvest green sugarcane and recover the residue, than to harvest burnt sugarcane. For the total Noodsberg

Mill area, there would be a saving of approximately R 12 000 000, if green sugarcane harvesting and sugarcane residue recovery operations were implemented.

The energy balance for the above-mentioned residue recovery route in the Noodsberg Mill area was determined and the results show that the energy in the sugarcane residue exceeds the energy expended during the sugarcane residue recovery operation (Table 6.6). Therefore, with regards to energy balances, this residue recovery operation is feasible.

Table 6.6 Noodsberg Mill area: Energy balance for chosen residue recovery route

		Energy (GJ)
Energy expended		
	Recovery operation	2 621
Energy acquired		
	Energy in residue	895 278
	Irrigation saving	0
	Total	895 278
Saving/Loss		+ 892 657

6.1.4 Sensitivity analysis of model inputs

A sensitivity analysis was conducted, to determine which model inputs have the most significant impact on the overall cost of sugarcane harvesting and residue recovery. A specific residue recovery route was selected and 35 model inputs for that route were analysed. The route selected was the manual harvesting of sugarcane, with the sugarcane and residue being placed in separate windrows. This was followed by residue collection, using a forage harvester, and the processing of the residue at a TOP plant, before it was transported to the mill.

The input values that were analysed, can be found in Tables 11.1 and 11.2 (Appendix C). Each input value was varied individually, to see what effect it would have on the overall cost for the residue recovery route. There were six variations used: 25%, 50%, 75%, 125%, 150% and 175% of the original value. The input value was flagged, if the percentage difference between the overall cost for the varied value and the original input value was greater than 10%, or less than −10%. If an input is flagged, it means that care should be taken when entering the input, as it will have a significant effect on the model output.

Eleven inputs were flagged as being sensitive variables in the model. These included the area from which sugarcane residue is to be collected, season length, sugarcane yield, mill overall time efficiency, fuel price, bulk density of harvested sugarcane, speed of infield transport, infield transport operating hours, distance from field to processing plant, percentage residue left for agronomic purposes and the residue recovery efficiency of the forage harvester. Each input depicted in Table 6.7 has either a linear or inverse relationship to the overall cost. Of the inputs that had a linear relationship to the overall cost, the area harvested had the most significant effect on the model output. Of the inputs that had an inverse relationship to the overall cost, the density of the whole-stick sugarcane had the greatest effect on the overall cost. The sensitivity analysis results can be found in Appendix C.

Table 6.7 Noodsberg Mill area: Input relationships to overall cost

Input	**Relationship to overall cost**	
	Linear	**Inverse**
Area harvested	x	
Sugarcane yield	x	
Fuel price	x	
Recovery efficiency of recovery machinery	x	
Season length		x
Mill overall time efficiency		x
Density of whole-stick sugarcane		x
Speed of infield transport		x
Field to processing plant distance		x
Infield transport operating hours		x
Percentage residue left infield for agronomy		x

6.2 Hypothetical Case Study: Large-scale Grower and Long-haul Distance

The model was run for a hypothetical scenario, which involved a grower on the North-Coast of KwaZulu-Natal. It was envisaged that the model should be run for a location that has different characteristics to the Noodsberg Mill area, as this will test whether the model is sensitive to a change in inputs. This would also determine whether the least-cost residue recovery route for the Noodsberg Mill supply area is different to the least-cost residue recovery route for a large-scale grower who is hauling over a long distance. The greatest difference between the Noodsberg and the hypothetical large-scale grower scenarios, is the distance to the mill. The sugarcane and residue from the large-scale grower is assumed to be delivered a distance of 153 km to the Felixton Mill, whilst the average field-to-mill distance for the Noodsberg Mill supply area was taken as 25 km.

The model was run for the hypothetical large-scale grower scenario, with the objective of obtaining a present-day comparison for the different residue recovery routes available. There are four major inputs/assumptions which have been made for this scenario, namely, the area supplies 300 000 tons of sugarcane to the Felixton Mill (Bezuidenhout, 2014a), has an average yield of 105 t/ha (Adendorff, 2014), is a distance of 153 km from the Felixton Mill (Bezuidenhout, 2014a) and has an average field-to-processing plant distance of 5 km. The inputs and assumptions that were used for this model run, can be found in Table 9.2 (Appendix A). The machinery used for each recovery route was assumed to be the same as for the Noodsberg case study and is listed in Table 6.2.

The field-to-processing plant distance was determined, using a different method to the Noodsberg Mill supply area case study. Unlike the Noodsberg scenario, where the sugarcane was assumed to surround the mill in a circular 1 km wide band, the hypothetical large-scale grower was assumed to have sugarcane in a 3 333 ha rectangular area (Bezuidenhout, 2014a). This area then has a processing plant-to-mill distance of 153 km. Figure 6.3 depicts the area under sugarcane and shows that the maximum field-to-processing plant distance is 5.27 km. Thus, although the average field-to-processing plant distance will be less than 5 km, the value which was used in the model was 5 km. This covers any irregularities in the shape of the sugarcane distribution.

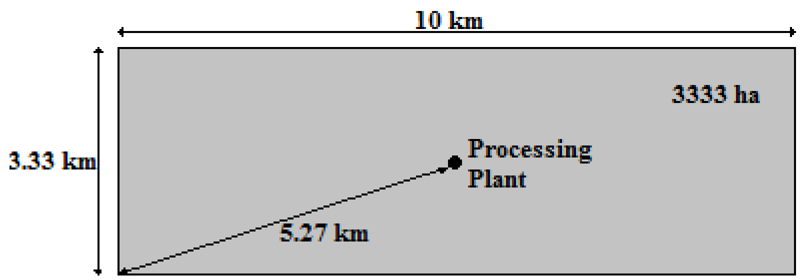

Figure 6.3 Large-scale grower: Diagram depicting field-to-processing plant distance

A flowchart of the costs involved for each residue recovery route can be found in Figure 6.4. The agronomic benefit of each route has been included in Figure 6.4; however, it does not form part of the residue recovery cost. As with the Noodsberg model run, the costs found in Figure 6.4 can be broken down further, into the costs represented in Tables 12.4, 12.5 and

12.6 (Appendix D). Only one method of manual harvesting (i.e. placing of sugarcane in stack), was considered, for the same reason as that explained in Section 6.1. The same machinery was utilised as in the Noodsberg model run (Table 6.2).

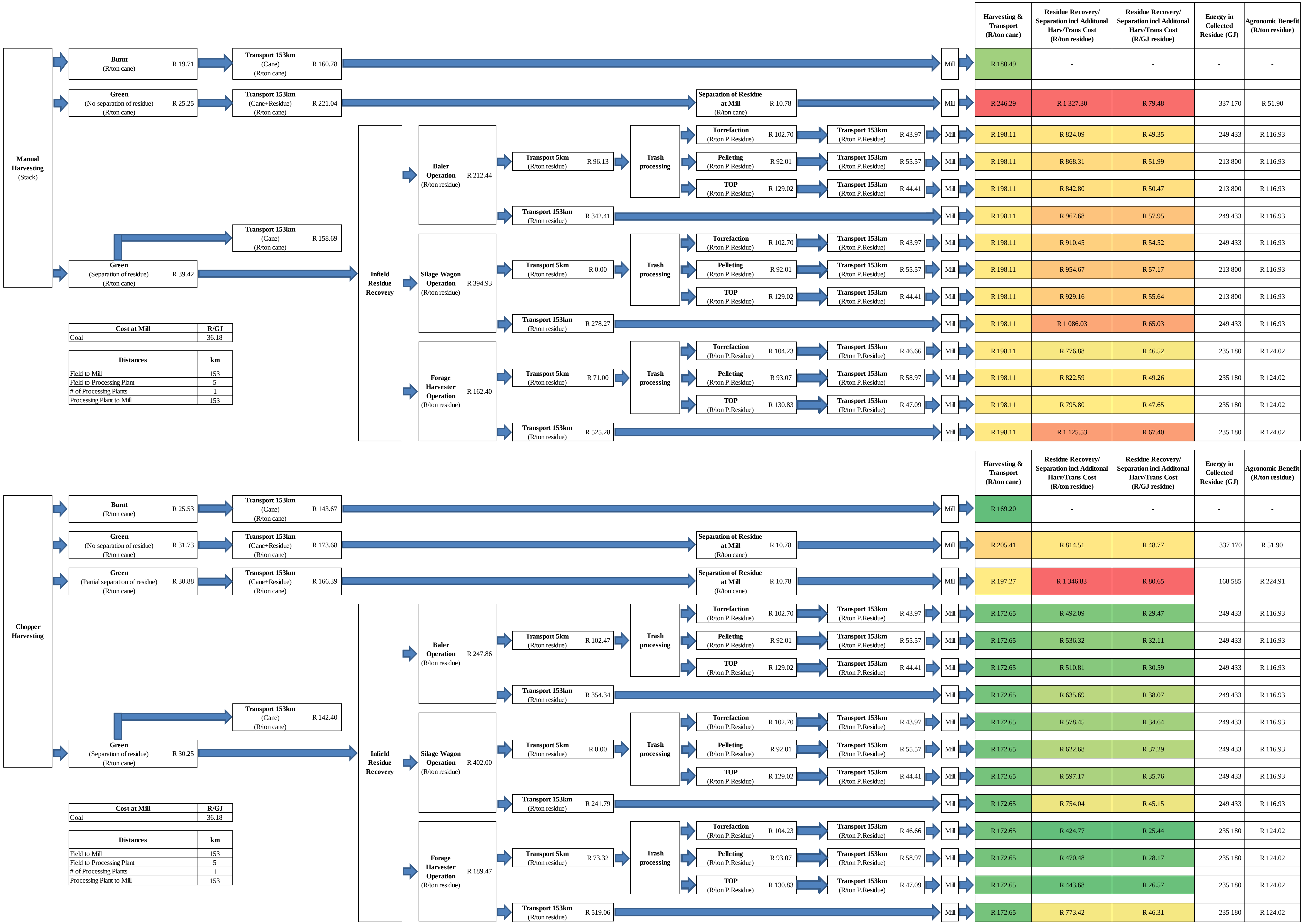

Figure 6.4 Large-scale grower: Residue recovery route cost flowchart

6.2.1 Output costs discussion

The following discussion relates to sugarcane residue recovery operations for the hypothetical large-scale grower scenario, and refers to Figure 6.4 and Table 6.8. The mill currently pays R 36.18/GJ for coal and is willing to pay the equivalent price for sugarcane residue. If the sugarcane grower can recover sugarcane residue for less than that, then there is a profit to be made and sugarcane residue recovery is economically feasible.

Table 6.8 Large-scale grower: Summary of least-cost residue recovery routes

Least-cost Residue Recovery Routes					Total Cost (R/GJ)
Rank	**Harvesting Method**	**Separation (Field/Mill)**	**Recovery Machinery**	**Residue Processing**	
1	CHffo	Field	Forage Harvester	Torrefaction	R 25.44
2	CHffo	Field	Forage Harvester	TOP	R 26.57
3	CHffo	Field	Forage Harvester	Pelleting	R 28.17
4	CHffo	Field	Baler	-	R 38.07
5	Man	Field	Forage Harvester	Torrefaction	R 46.52
6	Man	Field	Forage Harvester	TOP	R 47.65
7	CHffo	Mill	-	-	R 48.77
8	Man	Field	Forage Harvester	Pelleting	R 49.26
9	Man	Field	Baler	-	R 57.95
10	Man	Mill	-	-	R 79.48
where: Man = Manual Harvesting (Stack)					
CHffo = Chopper Harvester (fans fully on)					

The recovery routes presented in Table 6.8, which have a cost that is highlighted in green, are the routes which cost less than the coal equivalent cost. The least-cost residue recovery route occurs when the sugarcane is mechanically-harvested, with infield separation of residue. The residue is collected and taken to a torrefaction plant, where it is processed and then transported to the mill (R 25.44/GJ). The next best options would be to first process the residue at a TOP and then a pelleting plant. The reason for the difference in cost between the manually-harvested and the chopper harvester routes, where residue separation occurs infield, is the harvesting cost difference between these harvesting methods (R 198.11/t versus R 172.65/t of sugarcane).

Table 6.8 also gives an example of a recovery route, in which no processing occurs and where the residue is collected, using a baler, and transported to the mill. This cost is approximately R 13/GJ more than the least-cost recovery route, and thus shows the importance of processing, when there are large haulage distances involved. The cost of residue separation at the mill has been included in Table 6.8, to show that this residue recovery route is not always ideal. This route costs approximately R 23/GJ more than the least-cost recovery route. The reason why this route is so costly for this scenario, is that the sugarcane and residue are transported together, and the residue significantly reduces the bulk density of the sugarcane.

It is important to note that the only residue recovery routes with costs lower than the coal equivalent cost, are the routes which include residue processing. Thus, for the hypothetical large-scale grower scenario, every other route should not be considered, as these routes are not economically feasible, unless they are subsidised.

6.2.2 Overall cost and energy balance

As with the Noodsberg Mill case study, the overall effective cost and energy balance were determined for the hypothetical large-scale grower scenario. Again, it should be emphasized that these balances only consider the direct input costs and the full life cycle cost. Therefore, only simplistic balances are produced, however, these do serve the function of giving an indication of whether residue recovery may be financially viable. These balances were determined for the least-cost sugarcane residue recovery route. The chosen residue recovery route involved mechanically harvesting green sugarcane with a chopper harvester, collecting the residue with a forage harvester, processing the residue by torrefaction and then transporting the processed residue to the mill. It was assumed that the grower would receive a coal equivalent cost for the residue (R 600/t). The results from this investigation can be found in Table 6.9. For this case study, the model indicates that there could be a saving of approximately R 4 000 000, if green sugarcane harvesting and sugarcane residue recovery operations are implemented.

The energy balance for the above-mentioned residue recovery route for the large-scale grower scenario was determined and the results show that the energy in the sugarcane residue, and energy saved from a reduction in irrigation, exceed the energy expended during the sugarcane residue recovery operation (Table 6.10). Therefore, with regards to energy balances and energy available, this residue recovery operation is feasible.

Table 6.9 Large-scale grower: Cost feasibility of chosen residue recovery route

		Cost of operation
Burnt sugarcane harvesting		
	Chopper harvester	R 59 214 078.00
Green sugarcane harvesting		
	Mechanical harvesting (chopper harvester)	R 60 421 457.25
	Residue recovery (forage harvester)	R 3 286 884.54
	Residue processing (torrefaction)	R 1 487 547.62
	Residue value	- R 8 449 574.65
	Irrigation saving	- R 338 363.69
	Herbicide saving	- R 1 408 159.84
	Total	R 54 999 791.23
Saving/Loss		+ R 4 214 286.77

Table 6.10 Large-scale grower: Energy balance for chosen residue recovery route

		Energy (GJ)
Energy expended		
	Recovery operation	11 763
Energy acquired		
	Energy in residue	235 180
	Irrigation saving	3 748
	Total	238 928
Saving/Loss		+ 227 165

6.2.3 Sensitivity analysis of distance from the field to the mill

Running the model for the large-scale grower scenario has shown that residue processing can be beneficial when transporting residue over long distances. It is desirable to determine the distance at which residue processing becomes the least-cost residue recovery route, for the large-scale grower scenario. For this reason, a sensitivity analysis was conducted on the field-to-mill distance, in order to find this break-even point where residue processing forms part of the most economical residue recovery route.

In an effort to avoid over-complication, only three residue recovery routes (Route 1, Route 2 and Route 3) were considered during the sensitivity analysis. Route 1 involves separation at the mill, Route 2 includes residue recovery using a forage harvester, and Route 3 includes residue recovery using a forage harvester followed by residue processing by torrefaction. The results from the sensitivity analysis for these routes is shown in Figure 6.5. The results in Figure 6.5 suggest that, for distances equal to or greater than 35 km, Route 3 will be more economical. For the most part, Route 2 is more economical than Route 1. However, there are two distances at which Route 1 is more economical than Route 2, these being at 50 and 80 km. A reason for this could be that at these distances, every vehicle in the transport fleet is being fully utilised.

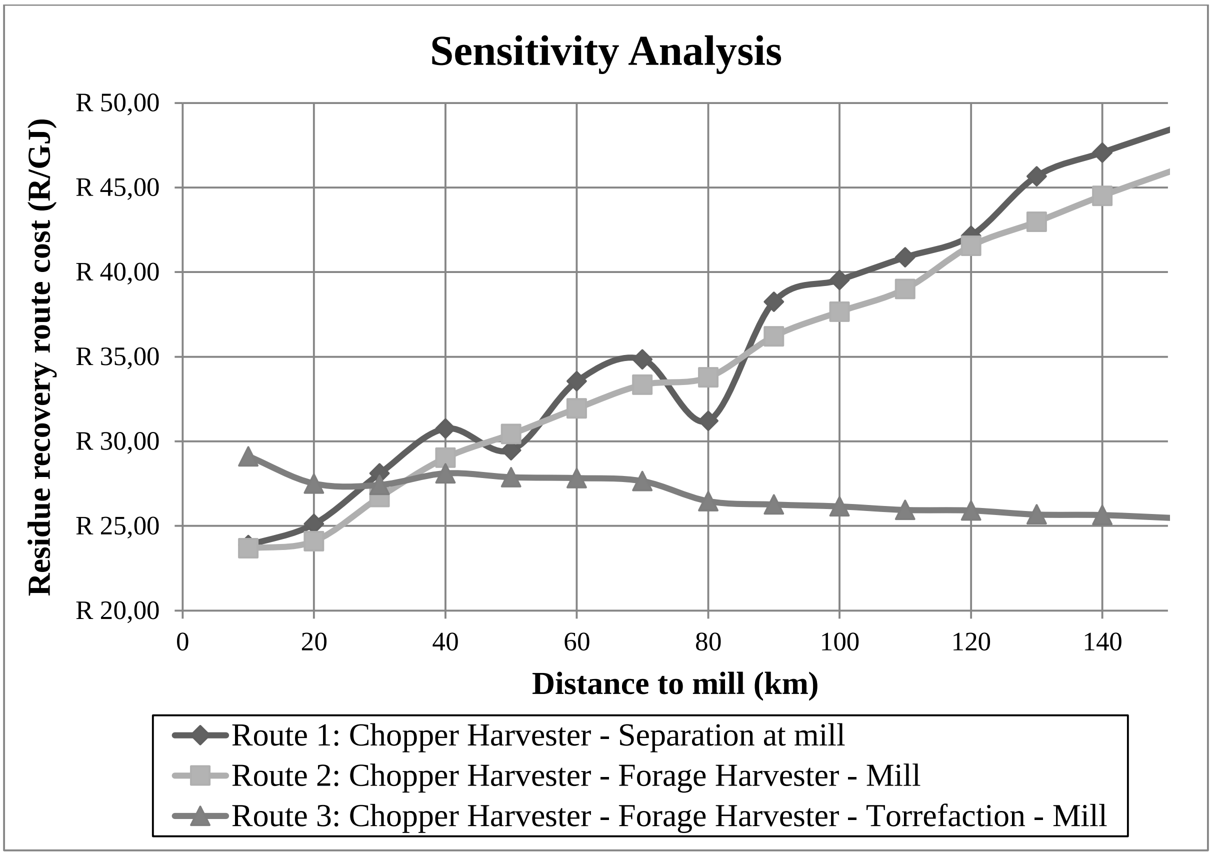

Figure 6.5 Large-scale grower: Sensitivity analysis

Figure 6.5 also suggests that if the residue recovery routes for this scenario do not include residue processing, it is more economical to separate the residue infield and collect it with a forage harvester, instead of separating the residue from the sugarcane at the mill. This applies for any field-to-mill distance.

7. DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

This chapter contains a discussion, conclusions, as well as recommendations for future research, pertaining to this project.

7.1 Discussion

Specific aspects of the sugarcane industry in South Africa were reviewed and it was noted that, if residue recovery were utilised, approximately 1 353 000 tons of residue per annum could be utilised at sugarcane mills. This value represents 3 111 900 GJ of energy, or 180.1 MW of electricity, per harvesting season. This represents a significant source of energy, and sugarcane residue should therefore be considered as a promising eco-friendly sustainable energy source.

If the residue is to be used for energy generation, it needs to be recovered from the field. A number of different residue recovery routes have been identified from the literature. A route comprises of a harvesting method, whether the residue is separated at the mill or infield, and if separated infield, it may include infield residue recovery methods, as well as residue processing. There are five major recovery routes that were identified, namely, Route A, Route B, Route C, Route D and Route E. Routes A, D and E involve the sugarcane and residue being separated at the mill. Routes B and C involve the sugarcane and residue being separated infield, and machinery is then required to recover the residue. The three residue recovery machines that were investigated were a baler, a forage harvester and a silage wagon. It may also be necessary to process the residue after infield recovery in order to increase the bulk density and thus reduce transport costs. The three processes that were investigated were torrefaction, pelleting and TOP.

In order to determine the economic feasibility of each residue recovery route, an economic costing model was required. A number of existing models were reviewed, with many of these being multi-component models that took into account the detailed operations for sugarcane production, harvesting and transport. The Economics of Sugarcane Production and Transport Calculator (EconoCane) was chosen as the best-suited model for this application, as it simulates many of the components of costing different residue recovery routes and it explicitly includes the simulation of the advantages to recovering sugarcane residue.

Additional components/operations were added to this model to ensure that the economics of each residue recovery route could be calculated. The operations that were added to the original model included the use of a forage harvester, a silage wagon and the processes of torrefaction, pelleting and TOP. Modifications have also been made to the chopper harvester component within the model.

When validated against residue recovery trials, which were conducted in the Noodsberg Mill supply area in the year 2009, the model proved to provide reasonable costs. The trial consisted of the sugarcane being mechanically harvested by a chopper harvester, with the fans fully operational, and the residue being recovered infield, using a baler. The exact costs for the machinery used during the trials could not be determined, and hence representative costs for 2009 were used during the model validation. This validation provided confidence in the use of this component of the model.

The model was then applied to two case studies. The first case study involved the Noodsberg Mill supply area. The mill is placed in a central position, with sugarcane delivered to the mill from all directions. The average field-to-mill distance is 25 km. If the residue recovery route included residue processing, then it was necessary to determine the number of processing plants were required. After an investigation, it was determined that the optimum number of processing plants required is four. This investigation assumed that the mill supply area was evenly distributed around the mill, which made it easier to determine the optimum number of processing plants required. However, this simplification makes assumptions regarding the mill area, which may not necessarily be true, as the harvested area may not be evenly distributed. Of the 27 different residue recovery routes evaluated, it was found that the least-cost route for the Noodsberg Mill supply area involves harvesting the sugarcane manually and separating the residue from the sugarcane at the mill. The cost and energy balances for this residue recovery route were both positive and therefore suggest that the use of residue as a fuel is feasible. A sensitivity analysis was conducted on 35 model inputs and, of these, 11 were found to have a significant impact on the model output costs. These included the area from which sugarcane residue is to be collected, season length, sugarcane yield, mill overall time efficiency, fuel price, bulk density of harvested sugarcane, speed of infield transport, infield transport operating hours, distance from field to processing plant, percentage residue left for agronomic purposes and the residue recovery efficiency of the forage harvester. Thus care needs to be taken when determining these for input into the model.

The second case study was a hypothetical scenario for a large-scale grower who hauls sugarcane a long distance to a mill. The sugarcane fields are estimated to be 153 km from the mill and, when residue processing is utilised, it was assumed that there was one centralised processing plant, with a field-to-processing plant distance of 5 km. Of the 27 different residue recovery routes, it was found that the least-cost route for this hypothetical large-scale grower involves mechanically harvesting the sugarcane, with the infield separation of the residue. The residue is collected, using a forage harvester, and taken to a torrefaction plant, where it is processed and then transported to the mill. The cost and energy balances for this residue recovery route both suggest that the use of residue as a fuel is feasible. A sensitivity analysis on the field-to-mill distance was conducted. For distances greater than 35 km, it was found that residue recovery routes that include processing, are the least cost. However, for distances less than 35 km, it is best not to include processing in the recovery route.

A direct comparison of the residue recovery costs for each case study is not recommended. If this is done, the results show that there are less costly routes for case study two, where the distance to the mill was 153 km, when compared to case study one. This seems counterintuitive. The reason for this is the cost of residue recovery includes the cost of the actual residue recovery operation, in addition to the additional harvesting cost incurred (green sugarcane harvesting cost, including transport, minus burnt sugarcane harvesting cost, including transport). Therefore, the burnt sugarcane harvesting cost (which includes the transport cost) is used as the baseline from which to calculate the additional harvesting cost. This burnt sugarcane harvesting and transport cost will differ for each case. For the Noodsberg case study, this cost was R 70.05, whilst for the second case study this cost was R 169.20. It is for this reason that residue recovery costs cannot be compared between differing case studies. These costs represent the additional cost which will be incurred when recovering residue for each case. What may be the lowest cost route for one case, may not be for another, as these cases may have differing baseline burnt harvesting costs.

When comparing the processing costs for each case study, the cost is found to be approximately three times higher for case study one, when compared to case study two. This may once again seem counterintuitive, as there should be better economy of scale in case study one. In case study one, the investigation found that four processing plants would be required for the area, these plants, however, do not work at full capacity. Only one processing plant is required for case study two, and theoretically this one plant could process the same volume of residue as the four plants in case study one. Thus the plants in case study one are underutilised. The requirement for four plants in case study one, also adds to the cost. These are the reasons for the higher processing costs for case study one.

There are a number of limitations to the model, one of which is that only one residue recovery route can be modelled at one time. Thus, the model is unable to make a comparison between the different recovery routes without the user manually specifying each recovery route individually and noting the individual costs. A limitation specific to residue separation at the mill, is the residue separation cost. This cost is taken as a constant rate per ton of sugarcane, no matter if the sugarcane arrives at the mill billeted or whole-stick. For each operation in a residue recovery operation, the user is able to specify which machinery was utilised. The user can choose machinery from the machine database in the model, but there may be cases where the required machine is not in the database. In this case, the user will have to manually enter input data specific to the desired machine, which can be time-consuming. Lastly, the fact that a whole-stick mechanical sugarcane harvesting option has not been incorporated in this model, could be a limitation, if this method of harvesting were to be employed in the future.

The model has a number of strengths. It is a complex model, as it has many inputs and it can replicate the many operations involved with sugarcane production, harvesting and transport well. The machine database within the model is extensive, which allows the user to choose from many machines. The major inputs for the model are located in one table, which helps to streamline the input process. The residue recovery route costs can be displayed as a cost per ton of residue, but also as a cost per unit energy, depending on the user preference.

When the EconoCane model is run, a number of assumptions are made and some of these assumptions can have a significant effect on the model output costs, as seen in the sensitivity analysis in Section 6.1.4. These assumptions can vary, depending on a number of factors, such as the growing conditions, area harvested and machinery used during the harvest and residue recovery operations. Thus, care should therefore be taken to ensure the best available assumptions are used, which would ensure the output costs are the best available estimates.

The processing of sugarcane residue by pelleting, torrefaction and TOP has yet to be implemented in South Africa. Therefore, when modelling these processes, many assumptions were made, but these can be easily changed as new information becomes available. The capital costs for these processing plants were found using the ratio between international costs for the plants and the cost of a pelleting plant in South Africa. Pelleting is a process which is employed in South Africa, although the pelleting of sugarcane residue has yet to be undertaken. It is for this reason that the capital costs for a pelleting plant, and thus a torrefaction and TOP plant, are the best available estimates and should not be taken as absolute values. The output cost estimates for these processes should, therefore, not be considered as absolute values, but rather as cost indications, which require further research.

As described in Section 4.2.5, the relationship between capital cost and production capacity for a pelleting plant was determined. A relationship depicting an economy-of-scale was expected; however, for the data which was available, a linear relationship is evident. This is not a realistic relationship, as there will always be an economy-of-scale relationship, when setting up any processing plant. By using a linear relationship between the capital requirements and output, the 'worst-case scenario' capital costs are determined. More research is required, to determine more reliable estimates for the different processing plant capital costs.

The output costs from the model, which are presented in this document, are given to two decimal places. This does not mean that the model is accurate to this level, but this is rather a consequence of mathematical formulae that are used in the model. It is important to remember that these are cost estimates and should not be considered to be completely accurate.

In the case where the user stipulates that there will be a residue blanket, the positive effect of leaving a residue blanket infield, will depend on the harvested area of sugarcane and its characteristics. These characteristics, such as irrigation requirements, or lack thereof, as well as the residue blanket density per hectare, will influence the irrigation and herbicide requirements, and thus the positive effect of the residue blanket will vary.

In some cases it has been found that residue processing is not economically feasible (Section 6.1). However, the aim of processing the residue is to increase its bulk density and reduce transport costs, thus processing only becomes viable when the residue is transported long distances. It is for this reason that residue processing should not be discarded, because it appears to be uneconomical, as it will be beneficial in some scenarios (e.g. see Section 6.2). Another aspect to consider is that if the residue is to be processed and sold commercially (e.g.

as briquettes), the resale value of the processed residue could potentially exceed the processing costs. For this project, the focus was on sugarcane residue as an additional source of energy at the mill, and therefore this option was not considered.

Another issue to consider is the composition of the residue which is delivered to the mill. There will be a difference in composition between residue which has been separated at the mill, and residue which has been separated and collected infield. If the residue is separated at the mill, this means that the sugarcane tops have been cut off and left infield. However, if the residue has been separated and collected infield, the residue that is collected will contain some sugarcane tops, which is undesirable.

7.2 Conclusions

The objectives for this project, which were set out in the Introduction, have been met. The potential energy available from sugarcane residue has been assessed, whilst taking into account the benefits of leaving a residue blanket in the field. The energy and costs of the different production and harvesting systems required to recover sugarcane residue and deliver it to a mill, have been investigated. These range from fully mechanised to manual harvesting systems.

Studies in Australia found that Route E, where a chopper harvester implements partial residue separation infield and the remaining residue is separated at the mill, is the least-cost residue recovery route. The second least-cost route involves no residue separation infield, but rather at the mill. This study found that the least-cost recovery route will depend on the characteristics of the residue recovery area. Different results were obtained for the two case studies that were performed, but generally, for distances shorter than 20 km, residue separation at the mill is best, for distances up to 35 km, the use of a forage harvester to collect residue infield is best, whilst for distances greater than 35 km, it is best to process the residue before transporting it that distance.

Although TOP has the highest energy density of the three processes considered, it was not found to be the least-cost process. This could be attributed to the high capital requirements of a TOP plant. Torrefaction was found to be the least-cost residue process.

As the production of sugar in South Africa becomes more costly and profit margins decrease, new income streams are required in the sugarcane industry. The use of residue as a fuel source could provide an additional income source and help to sustain the industry. It is for this reason that the findings of this study are of great relevance. The model which has been developed, will be able to give sugarcane growers an indication of the economic feasibility of residue recovery in the different sugarcane growing areas of South Africa, and this could serve as a tool to promote residue recovery in areas where residue recovery was assumed to not be feasible. Time and money can also be saved, when determining the least-cost residue recovery route, as it does not have to be determined by trial and error, but rather, the model can be used to indicate the least-cost recovery routes.

7.3 Recommendations for Future Research

The model which has been adopted and adapted during this study, does not take into account the storage of sugarcane residue. As the sugarcane residue will only be collected over a season length of approximately 220 days, the rest of the year the mill will have to receive residue from a stockpile, or be supplemented by other fuel sources, such as coal or wood. This scenario is not accounted for in the model and the future development of the model should consider the stockpile/supplementation of sugarcane residue during the off-season.

Another piece of machinery which could form part of a future residue recovery route is an automatic bale loading trailer, which is trailed behind the baler. The bales are picked up immediately after being formed and can thus be transported to the field edge, or a nearby transloading zone, for transfer to the road haulage vehicle. This eliminates the requirement for additional infield transport of bales.

For the model to become more accurate and reliable, improved capital cost values for pelleting/torrefaction/TOP processing plants need to be determined. In addition, a more comprehensive cost system for residue separation at the mill is required.

The model should be validated against residue recovery trial results that become available, both from South African and international trials. This would help ensure that the model is calculating realistic current real-world costs and thus ensure the model’s validity.

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9. APPENDIX A: INPUT VALUES

Appendix A contains Tables 9.1 to 9.8, which refer to the inputs/input values which have been utilised in the model.

Table 9.1 Example of dropdown menu options (Lubbe *et al.*, 2013)

Tractor	**Baler**	**Forage Harvester**	**Silage Wagon**	**Loader**	**Infield Trailer**	**Truck**	**Road Trailer**
Ag:35kW-2WD	SB: Class 3 (360*460cm)	Mounted 1-row	7 cubic m	Bell: 125 (3)	Ag: 1 basket	8t	22t T/tr spiller
Ag:45kW-2WD	SB: Class 3 (360*480cm)	Mounted 2-row	13 cubic m	Bell: 125 (4)	Ag: 1 side SLT	14t	30t T/tr spiller
Ag:55kW-2WD	SB: Class 4 (360*460cm)	Mounted 4-row	15 cubic m	Bell: 220 (4)	Ag: Dbl box	T/trac 250kW	34t T/tr spiller
Ag:55kW-FWA	SB: Class 4 (360*490cm)	Mounted 1.1m	17 cubic m	Slew: Sml	Ag: Dbl side SLT	T/trac 300kW	34t R&Db spiller
Ag:60kW-2WD	SB: 1200*700cm	Mounted 1.6m	20 cubic m	Slew: JD1850	Ag: 6T Tip	R&Db 300kW	
Ag:60kW-FWA	SB: 1200*1000cm	Trailed 2-row		Slew: JD2254	Ag: 10T Tip		
Ag:75kW-2WD	RB: 0.7m	Trailed 3-row			H: 15T Spiller		
Ag:75kW-FWA	RB: 1.2m	Trailed 1.7m			H: 2x14T Spiller		
Ag:85kW-FWA	RB: 1.5m	Trailed 1.8m					
H:55kW-2WD	RB: 1.6m	Trailed 2.1m					
H:60kW-2WD		Trailed 2.2m					
H:75kW-2WD		Trailed 2.7m					
H:95kW-2WD							
H:138kW-2WD							
H:95kW-FWA							
H:138kW-FWA							
H:150kW-FWA							

Table 9.2 Model inputs: General

Parameter	Range	Units	References	Noodsberg	Hypothetical Case Study
General					
Area under sugarcane		ha	(Bezuidenhout, 2014a; de Lange, 2014)	30500	3333
% harvested per year	45% - 90%	%	(Bezuidenhout, 2014a; de Lange, 2014)	52%	100%
Season length: Sugarcane harvesting	224 - 238	days	(Smith *et al.*, 2012; de Lange, 2013)	220	217
Season length: Processing of residue		days	User input	220	217
Sugarcane yield per hectare	58 - 90	t/ha	(de Lange, 2013; Adendorff, 2014)	84	105
Mill: Overall time efficiency		%	(Smith *et al.*, 2012; de Lange, 2013)	81.0%	68.2%
Cost of residue separation at mill	R 10.78	R/t sugarcane	(Norris, 2008)	R 10.78	R 10.78
Residue value at mill	300 - 600	R/t	Coal equivalent	300	500
Interest rate		%	User input	6%	6%
Fuel price		R/l	(Engen, 2014)	13.29	13.29
Electricity cost		R/kWh	(Eskom, 2013; Bezuidenhout, 2014b)	0.54	0.54
Harvested sugarcane					
Density: Clean billeted sugarcane	350 - 410	kg/m^3	(Marchi *et al.*, 2005)	410	410
Density: Billeted sugarcane with residue	240 - 250	kg/m^3	(Marchi *et al.*, 2005)	250	250
Density: Billeted sugarcane with residue (Partial separation)	270 - 280	kg/m^3	(Marchi *et al.*, 2005)	280	280
Density: Clean whole-stick sugarcane	300 - 350	kg/m^3	(Norris, 2008)	320	320
Density: Whole-stick sugarcane with residue	220 - 230	kg/m^3	(Marchi *et al.*, 2005)	225	225
Transport					
Contractor (Sugarcane)			User input	No	No
Contractor (Sugarcane residue)			User input	No	No
Contractor (Processed sugarcane residue)			User input	No	No
Contract rate (Sugarcane)	35 - 90	R/t	(de Lange, 2014)	-	-
Contract rate (Residue)	35 - 90	R/t	(de Lange, 2014)	-	-
Contract rate (Processed biomass)		R/t	User input	-	-
Speed and distances					
Speed: Infield transport		km/h	(de Lange, 2014)	10	10
Speed: Road transport		km/h	(de Lange, 2014)	60	60
Distance: Field to mill	≈ 25	km	(Bezuidenhout, 2014a; de Lange, 2014)	25	153
Distance: Field to processing plant		km	User input	20	5
Distance: Processing plant to mill		km	User input	25	153
Operating hours per day					
Chopper harvester		h	User input	10	10
Residue recovery equipment		h	User input	10	10
Infield loading		h	User input	10	10
Infield transport		h	User input	10	10
Transloading		h	User input	20	20
Road transport		h	User input	20	20
Processing plant		h	User input	24	24
Residue processing					
Weight loss during torrefaction		%	(Wang *et al.*, 2013)	30%	30%
Bio-char bulk density		kg/m^3	(Uslu *et al.*, 2008)	230	230
Pellet bulk density		kg/m^3	(Uslu *et al.*, 2008)	575	575
TOP bulk density		kg/m^3	(Uslu *et al.*, 2008)	800	800
Residue recovery					
% area to collect residue		%		100%	100%
% Residue left infield for agronomy		%	(Brouckaert, 2014)	50%	50%
Recovery efficiency (Baler)		%	(de Carvalho Macedo *et al.*, 2001)	70%	70%
Recovery efficiency (Forage harvester)		%	(Hassuani *et al.*, 2005)	66%	66%
Recovery efficiency (Silage wagon)		%	(Hassuani *et al.*, 2005)	70%	70%
Residue bulk density (Loose)	50 - 65	kg/m^3	(Smithers, 2014)	55	55
Residue bulk density (Forage harvester)		kg/m^3	(de Beer *et al.*, 1996; Smithers, 2014)	65	65
Residue bulk density (Silage wagon)		kg/m^3	(Pottinger, 2013)	140	140

Table 9.3 Model inputs: Manual harvesting

Inputs	Range	Units	Reference	Noodsberg	Hypothetical Case Study
Cutters					
Tonnage per day					
Burnt					
Windrow	6	t/day	(Meyer *et al.*, 2005b)	6	6
Stack	4.9	t/day	(Meyer *et al.*, 2005b)	4.9	4.9
Bundle	6	t/day	(Meyer *et al.*, 2005b)	6	6
Green					
Windrow	4.2	t/day	(Meyer *et al.*, 2005b)	4.2	4.2
Stack	3.4	t/day	(Meyer *et al.*, 2005b)	3.4	3.4
Bundle	4.2	t/day	(Meyer *et al.*, 2005b)	4.2	4.2
Wage (R/t)					
Burnt	16	R/t	(Wynne and van Antwerpen, 2004)	16	16
Green (No separation)	20.3	R/t	(Wynne and van Antwerpen, 2004)	20.3	20.3
Green (separation)	32	*double burnt sugarcane wage	(Norris, 2014)	32	32
Induna					
Cutters per Induna	25		(Wynne and van Antwerpen, 2004)	25	25
Wage	100	R/day	(Wynne and van Antwerpen, 2004)	100	100
Labour transport					
Tractor hours per day	0.66	h	(Wynne and van Antwerpen, 2004)	0.66	0.66
Cost	110.28	R/h	(Wynne and van Antwerpen, 2004)	110.28	110.28
Labour tools					
Knives per cutter	5		(Wynne and van Antwerpen, 2004)	5	5
Knife price	R17.90		(Wynne and van Antwerpen, 2004)	R 17.90	R 17.90
Files per cutter	4		(Wynne and van Antwerpen, 2004)	4	4
File price	R 13.80		(Wynne and van Antwerpen, 2004)	R 13.80	R 13.80
Smocks per cutter	2		(Wynne and van Antwerpen, 2004)	2	2
Smock price	R 23.50		(Wynne and van Antwerpen, 2004)	R 23.50	R 23.50
Management concession	15 %	of harvesting cost (R/t)	(Wynne and van Antwerpen, 2004)	15%	15%

Table 9.4 Model inputs: Baling

Inputs	Range	Units	Reference	Noodsberg	Hypothetical Case Study
Raking operation					
Width of cut	2.5	m	User input	2.5	2.5
Row length	250	m	User input	250	250
Operating speed	6	km/h	User input	6	6
Average turn time	0.2	min	User input	0.2	0.2
Field efficiency	95	%	User input	95	95
Machine efficiency	70-90	%	(ASABE, 2011)	90	90
Baling operation					
Twine cost	12 to 18	R/t	(Wynne and van Antwerpen, 2004; de Lange, 2014)	12	12
Width of cut	2.5	m	User input	2.5	2.5
Row length	250	m	User input	250	250
Operating speed	0.82 - 2.33	km/h	(Paul and Krishnamurthi, 2007; Lyne, 2014)	4	4
Average turn time	0.5	min	User input	0.5	0.5
Recovery efficiency	70	%	(de Carvalho Macedo *et al.*, 2001)	70	70

Table 9.5 Model inputs: Chopper harvester

Inputs	Range	Units	Reference	Noodsberg	Hypothetical Case Study
Chopper harvester					
Width of cut	1.2	m	User input	1.2	1.2
Row length	150	m	User input	150	150
Operating speed	4.5 - 6.5	km/h	User input	4.5: green cane, 6.5: burnt cane	4.5: green cane, 6.5: burnt cane
Average turn time	1.5	min	User input	1.5	1.5
Purchase price	1 380 000	R	(Lubbe *et al.*, 2013)	1 380 000	1 380 000
Interest rate	7%	%	(Lubbe *et al.*, 2013)	7%	7%
Operator	75 135	R	(Lubbe *et al.*, 2013)	75 135	75 135
Licence and insurance	13 800	R	(Lubbe *et al.*, 2013)	138 000	138 000
Life	12 000	h	(Lubbe *et al.*, 2013)	12 000	12 000
Tyres:-					
Price	35 000	R	(Lubbe *et al.*, 2013)	35 000	35 000
Life	6 000	h	(Lubbe *et al.*, 2013)	6 000	6 000
Fuel :-					
Litres/hour	25	l/h	(Lubbe *et al.*, 2013)	25	25
Fuel cost	13.29	R/l	(Lubbe *et al.*, 2013)	13.29	13.29
Maintenance:					
% Price	170	%	(Lubbe *et al.*, 2013)	170	170
Max. Life	10	yr	(Lubbe *et al.*, 2013)	10	10
Resale :-					
Base %	45	%	(Lubbe *et al.*, 2013)	45	45
Base age	5	yr	(Lubbe *et al.*, 2013)	5	5
Yearly %	5	%	(Lubbe *et al.*, 2013)	5	5
Minimum price	10	%	(Lubbe *et al.*, 2013)	10	10

Table 9.6 Model inputs: Silage wagon

Inputs	Range	Units	Reference	Noodsberg	Hypothetical Case Study
Raking operation					
Width of cut	2.5	m	User input	2.5	2.5
Row length	250	m	User input	250	250
Operating speed	6	km/h	User input	6	6
Average turn time	0.2	min	User input	0.2	0.2
Field efficiency	95	%	User input	95	95
Machine efficiency	90	%	User input	90	90
Silage wagon operation					
Width of cut	2.5	m	User input	2.5	2.5
Row length	250	m	User input	250	250
Operating speed	6	km/h	User input	6	6
Average turn time	0.5	min	User input	0.5	0.5
Field efficiency	55-90	%	(ASABE, 2011)	80	80
Machine efficiency	70	%	(Hassuani *et al.*, 2005)	70	70

Table 9.7 Model inputs: Forage harvester

Inputs	Range	Units	Reference	Noodsberg	Hypothetical Case Study
Raking operation					
Width of cut	2.5	m	User input	2.5	2.5
Row length	250	m	User input	250	250
Operating speed	6	km/h	User input	6	6
Average turn time	0.2	min	User input	0.2	0.2
Field efficiency	95	%	User input	95	95
Machine efficiency	70-90	%	(ASABE, 2011)	90	90
Forage harvesting operation					
Width of cut	2.5	m	User input	2.5	2.5
Row length	250	m	User input	250	250
Operating speed	6	km/h	User input	6	6
Average turn time	0.5	min	User input	0.5	0.5
Field efficiency	60-85	%	(ASABE, 2011)	80	80
Machine efficiency	66	%	(Hassuani *et al.*, 2005)	66	66

Table 9.8 Model inputs: Transport and loading

Inputs	Range	Units	Reference	Noodsberg	Hypothetical Case Study
Transport					
Infield transport					
Loading rate	Bell 125 = 20; Bell 220 = 25; Slew sml/JD1850 = 25; Slew JD2254 = 30	t/h	(Tweddle, 2014)	Bell 125 (3)	Bell 125 (3)
Volume of trailer	H: 2x14T Spiller = 106; H: 15T Spiller = 53; 10T Tip = 23.5; Ag:1 basket/Ag:1 side SLT/Ag:Dbl box/Ag:Dbl side SLT = 15	m^3	(Landmech, 2014; Unicab, 2014)	15 m^3	15 m^3
Max payload	Ag:1 basket/Ag:1 side SLT/Ag:Dbl box/Ag:Dbl side SLT = 8; Ag: 6T Tip = 6; Ag: 10T Tip = 10; H: 15T Spiller = 15; H: 2x14T Spiller = 22	t	(Lubbe *et al.*, 2013)	8 t	8 t
Road transport					
Loading rate	Bell 125 = 20; Bell 220 = 25; Slew sml/JD1850 = 25; Slew JD2254 = 30	t/h	(Tweddle, 2014)	Bell 125 (3)	Bell 125 (3)
Volume of trailer	105	m^3	(Unicab, 2014)	105 m^3	105 m^3
Max payload	22t T/tr spiller = 22; 30t T/tr spiller = 30; 34t T/tr spiller = 34; 34t R&Db spiller = 34	t	(Landmech, 2014; Unicab, 2014)	30 t	30 t

10. APPENDIX B: FORMULAE

Appendix B contains the mathematical equations which were utilised in the model. These equations have been placed into five categories, which can be found in Sections 10.1 to 10.5.

10.1 General

$$Y = \frac{y_t}{A_h} \tag{10.1}$$

where

Y = total annual sugarcane yield [t/ha],

Y_t = total annual sugarcane yield [t], and

A_h = annual area harvested [ha].

$$A_r = A_h \times A_{r\%} \tag{10.2}$$

where

A_r = annual area from which residue collected [ha], and

$A_{r\%}$ = percentage of annual area harvested from which residue collected [%].

$$Y_{rd} = (Y_{rw} \times (1 - MC_r)) - RB \tag{10.3}$$

where

Y_{rd} = average dry residue yield per hectare [t/ha],

Y_{rw} = average wet residue yield per hectare [t/ha],

MC_R = moisture content of residue [%], and

RB = residue blanket density [t/ha].

$$Y_{rt} = Y_{rd} \times A_r \tag{10.4}$$

where

Y_{rt} = total annual dry residue yield [ton].

$$A_{hd} = \frac{A_r}{T_d} \tag{10.5}$$

where

A_{hd} = area from which residue collected per day [ha], and

T_d = harvesting period length [days/yr].

$$Y_{rtx} = Y_{rt} \times T_d \frac{Y_{rt}}{T_d} \tag{10.6}$$

where

Y_{trx} = total daily residue yield [t].

10.2 All Machinery

These are the Microsoft Excel formulae which are utilised. There are some Excel functions included in these formulae which are explained below.

$$L_{calc} = TRUNC\left(\frac{\left(\frac{L_h}{T_h}+0.005\right)100}{100}\right) \quad (10.7)$$

where

L_{calc} = calculated machine life [yr],

$TRUNC$ = returns a number truncated to a specified number of digits,

L_h = expected machine life [hr], and

T_h = working hours per year [hr].

$$L_{act} = L_{calc} \times (L_{calc} <= L_{max}) + L_{max} \times (L_{calc} > L_{max}) \quad (10.8)$$

where

L_{act} = actual machine life [yr], and

L_{max} = maximum machine life [yr].

$$R_{calc} = TRUNC\left(\left(\left(R_{bf} + (R_{ba} - L_{act}) \times R_{yf}\right) \times P_p\right) + 0.5\right) \quad (10.9)$$

where

R_{calc} = calculated resale value of machine,

R_{bf} = resale base fraction,

R_{ba} = resale base age [yr],

R_{yf} = resale yearly fraction, and

P_p = purchase price of machine.

$$R_{act} = R_{calc} \times (R_{calc} >= P_{min}) + P_{min} \times (R_{calc} < P_{min}) \quad (10.10)$$

where

R_{act} = actual resale value of machine [yr], and

P_{min} = minimum resale price of machine [yr].

$$P_{min} = \frac{R_m \times P_p}{100} \quad (10.11)$$

where

R_m = minimum resale cost as percentage of purchase price [%].

$$D = TRUNC\left(\left(\frac{P_p - P_t - R_{act}}{L_{act}}\right) + 0.5\right) \quad (10.12)$$

where

D = depreciation,

P_t = price of tyres.

$$I = TRUNC\left(\left(\frac{(P_p + R_{act}) \times I_r}{2}\right) + 0.5\right) \quad (10.13)$$

where

I = interest, and

I_r = interest rate [%].

$$F_c = TRUNC\big((D + I + O + LI) + 0.5\big) \quad (10.14)$$

where

F_c = fixed cost per year,

O = operator cost per year, and

LI = license and insurance per year.

$$P_{ta} = TRUNC\left(\frac{P_t \times T_h}{L_t}\right) \quad (10.15)$$

where

P_{ta} = annual tyre cost, and

L_t = life of tyres [hr].

$$P_{fa} = F_c \times T_h \times P_f \quad (10.16)$$

where

P_{fa} = annual fuel cost,

F_c = fuel consumption [l/hr], and

P_f = price of fuel [R/l].

$$P_{ea} = E_c \times P_e \times T_h \quad (10.17)$$

where

P_{ea} = annual electricity cost,

E_c = electricity consumption [kWh/t_{input}],

P_e = price of electricity [R/kWh].

$$P_m = \frac{P_p \times M_f \times T_h}{L_h} \quad (10.18)$$

where

M_f = expected maintenance as fraction of purchase price.

$$P_{tac} = F_c + P_{ta} + P_{fa} + P_m \quad (10.19)$$

where

P_{tc} = total annual costs.

$$P_{tch} = TRUNC\left(\frac{P_{tac}}{T_h} + 0.005\right) \quad (10.20)$$

where

P_{tch} = total annual cost per hour.

$$P_{tctr} = TRUNC\left(\frac{\left(\frac{P_{tch} \times T_h \times N_m \times 100}{Y_{rt}}\right) + 0.5}{100}\right) \quad (10.21)$$

where

N_m = number of machines.

10.3 Tractor, Rake, Baler, Forage Harvester and Silage Wagon

$$W_w = RW_s \times RW_{\#w} \quad (10.22)$$

where

W_w = width of each windrow [m],

RW_s = row spacing [m], and

$RW_{\#w}$ = number of rows per windrow.

$$W_p = \frac{W_w}{X_w} \quad (10.23)$$

where

W_p = average width of cut pass [m], and

X_w = number of passes per windrow.

$$RO_{tt} = \frac{10000}{\left(\frac{W_p}{S_o \times 1000}\right)} \quad (10.24)$$

where

RO_{tt} = raking operation travel time [hr/ha], and

S_o = operating speed [km/hr].

$$RO_{ta} = \frac{10000}{\left(\frac{RO_l}{W_p}\right) \times T_{tt} \times 60} \quad (10.25)$$

where

RO_{ta} = raking operation turn time [hr/ha],

RO_l = row length [m], and

T_{tt} = average turn time [min].

$$RO_h = \frac{RO_{tt} + RO_{ta}}{\left(\frac{RO_{fe}}{100}\right)} \quad (10.26)$$

where

RO_h = raking operation operating hours [hr/ha], and

RO_{fe} = raking operation field efficiency [%].

$$RO_{moh} = \frac{T_d - RO_{ttm}}{RO_h} \quad (10.27)$$

where

RO_{moh} = machine output [ha/day], and

RO_{ttm} = travel time [hr/day/machine].

$$T_h = (A_r \times RO_h) + (T_d + RO_{ttm}) \quad (10.28)$$

$$RO_{mot} = \frac{Y_{rt}}{T_h} \quad (10.29)$$

where

RO_{mot} = machine output [t/day], and

$$N_m = ROUNDUP\left(\frac{\left(\frac{A_d}{RO_{moh}}\right)}{\left(\frac{M_e}{100}\right)}, 0\right) \quad (10.30)$$

where

A_d = area harvested per day [ha/day], and

M_e = machine efficiency [%].

10.4 Infield Transport, Silage Wagon and Road Transport

$$TR_{pv} = BD_r \times TR_v \quad (10.31)$$

where

TR_{pv} = maximum payload of transport by volume [t],

BD_r = residue bulk density [kg/m^3], and

TR_v = maximum volume of transport [m^3].

$$TR_{pa} = TR_{pv} \times \left(TR_{pv} <= TR_{pam}\right) + TR_{pam} \times (TR_{pv} > TR_{pam}) \quad (10.32)$$

where

TR_{pa} = actual payload [t], and

TR_{pam} = maximum allowable payload [t].

$$TR_{lt} = \frac{TR_{pa}}{TR_{lr}} \times 60 \quad (10.33)$$

where

TR_{lt} = loading time of transport [min], and

TR_{lr} = loading rate [t/hr].

$$TR_{ut} = \frac{TR_{pa}}{TR_{ur}} \times 60 \quad (10.34)$$

where

TR_{ut} = unloading time of transport [min], and

TR_{ur} = unloading rate [t/hr].

$$TR_{ct} = \left(\frac{60}{S_o} \times TR_d \times 2\right) + TR_{lt} + TR_{ut} \quad (10.35)$$

where

TR_{ct} = transport cycle time [min], and

TR_d = distance per cycle [km].

$$TR_{tr} = TRUNC\left(\frac{\left(\frac{Y_{trx}}{TR_{pa}}+0.005\right)\times 100}{100}\right) \quad (10.36)$$

where

TR_{tr} = trips required per day.

$$TR_{tp} = TRUNC\left(\frac{\left(\frac{\left(\frac{T_h}{T_d}\right)}{TR_{ct}}+0.005\right)\times 100}{100}\right) \quad (10.37)$$

where

TR_{tp} = trips possible per day.

$$TR_{vr} = TRUNC\left(\frac{TR_{tr}}{TR_{tp}} + 0.99\right) \tag{10.38}$$

where

TR_{vr} = vehicles required.

10.5 Loading Zone

$$LZ_h = TRUNC\left(\left(\frac{\left(\left(\frac{Y_{rt}}{TR_{lr}}\right) \times 100 + 0.5\right)}{100}\right) \times 2\right) \tag{10.39}$$

where

LZ_h = loading hours per year [hr].

11. APPENDIX C: SENSITIVITY ANALYSIS

Appendix C contains the results (Tables 11.1 and 11.2) from the sensitivity analysis conducted in Section 6.1.4.

Table 11.1 Sensitivity analysis

Parameter	Original Value	Original Cost (Mrands)	-75% Original Value		-50% Original Value		-25% Original Value	
			Cost (Mrands)	% Change	Cost (Mrands)	% Change	Cost (Mrands)	% Change
Area residue collected from/annum (ha)	30 500	R 152.44	R 39.48	-74%	R 77.06	-49%	R 114.64	-25%
Season length (days)	220	R 152.44	R 214.62	41%	R 172.98	13%	R 158.54	4%
Sugarcane yield (t/ha)	84	R 152.44	R 47.10	-69%	R 82.12	-46%	R 117.20	-23%
Mill OTE (%)	81	R 152.44	R 208.49	37%	R 170.38	12%	R 157.83	4%
Interest rate (%)	6	R 152.44	R 151.31	-1%	R 151.67	-1%	R 152.04	0%
Fuel price (R/l)	13.29	R 152.44	R 125.78	-17%	R 134.65	-12%	R 143.54	-6%
Electricity price (R/kWh)	0.54	R 152.44	R 143.58	-6%	R 146.53	-4%	R 149.48	-2%
Density: Whole-stick sugarcane with residue (kg/m^3)	320	R 152.44	R 241.11	58%	R 180.85	19%	R 160.50	5%
Speed: Infield transport (km/h)	10	R 152.44	R 169.71	11%	R 157.93	4%	R 154.19	1%
Speed: Road transport (km/h)	60	R 152.44	R 161.21	6%	R 155.06	2%	R 153.46	1%
Distance: Field to processing plant (km)	20	R 152.44	R 198.29	30%	R 167.07	10%	R 159.80	5%
Distance: Processing plant to mill (km)	25	R 152.44	R 152.14	0%	R 152.14	0%	R 152.43	0%
Operating hours: Infield transport (h)	10	R 152.44	R 174.99	15%	R 158.71	4%	R 154.36	1%
Operating hours: Forage harvester (h)	10	R 152.44	R 153.63	1%	R 153.60	1%	R 152.80	0%
Operating hours: TOP plant (h)	24	R 152.44	R 152.44	0%	R 152.44	0%	R 152.43	0%
% Residue left infield for agronomy (%)	50	R 152.44	R 168.81	11%	R 163.26	7%	R 157.89	4%
Recovery efficiency: Forage harvester (%)	66	R 152.44	R 136.11	-11%	R 141.52	-7%	R 147.01	-4%
Residue bulk density: Forage harvester (kg/m^3)	65	R 152.44	R 165.75	9%	R 157.03	3%	R 153.97	1%
License and Insurance (% purchase price) (Forage harvester)	4 693	R 152.44	R 152.41	0%	R 152.42	0%	R 152.43	0%
Maintenance % (Forage harvester)	80	R 152.44	R 150.28	-1%	R 151.00	-1%	R 151.72	0%
Max life (yr) (Forage harvester)	15	R 152.44	R 152.44	0%	R 152.44	0%	R 152.44	0%
Resale: Base % (Forage harvester)	35	R 152.44	R 153.34	1%	R 153.04	0%	R 152.74	0%
Resale: Base age (yr) (Forage harvester)	5	R 152.44	R 153.08	0%	R 152.87	0%	R 152.65	0%
Resale: Yearly % (Forage harvester)	5	R 152.44	R 152.95	0%	R 152.78	0%	R 152.61	0%
Resale: Minimum price % (Forage harvester)	10	R 152.44	R 152.44	0%	R 152.44	0%	R 152.44	0%
Weight loss: TOP (%)	30	R 152.44	R 153.54	1%	R 153.17	0%	R 152.81	0%
Biomass bulk density: TOP (kg/m^3)	800	R 152.44	R 152.44	0%	R 152.44	0%	R 152.44	0%
License and Insurance (% purchase price) (TOP plant)	21 689	R 152.44	R 152.37	0%	R 152.39	0%	R 152.41	0%
Maintenance % (TOP plant)	5	R 152.44	R 152.39	0%	R 152.41	0%	R 152.42	0%
Max life (yr) (TOP plant)	15	R 152.44	R 152.61	0%	R 152.49	0%	R 152.45	0%
% downtime per year (TOP plant)	6	R 152.44	R 152.44	0%	R 152.44	0%	R 152.44	0%
Resale: Base % (TOP plant)	0	R 152.44	R 152.30	0%	R 152.30	0%	R 152.30	0%
Resale: Base age (yr) (TOP plant)	0	R 152.44	R 152.44	0%	R 152.44	0%	R 152.43	0%
Resale: Yearly % (TOP plant)	0	R 152.44	R 152.44	0%	R 152.44	0%	R 152.44	0%
Resale: Minimum price % (TOP plant)	10	R 152.44	R 152.40	0%	R 152.41	0%	R 152.42	0%

Table 11.2 Sensitivity analysis continued

Parameter	Original Value	Original Cost (Mrands)	+25% Original Value		+50% Original Value		+75% Original Value	
			Cost (Mrands)	% Change	Cost (Mrands)	% Change	Cost (Mrands)	% Change
Area residue collected from/annum (ha)	30 500	R 152.44	189.847	25%	227.269	49%	265.148	74%
Season length (days)	220	R 152.44	148.567	-3%	145.638	-4%	144.262	-5%
Sugarcane yield (t/ha)	84	R 152.44	187.344	23%	222.314	46%	257.622	69%
Mill OTE (%)	81	R 152.44	149.307	-2%				
Interest rate (%)	6	R 152.44	152.816	0%	153.195	0%	153.575	1%
Fuel price (R/l)	13.29	R 152.44	151.295	-1%	170.182	12%	179.07	17%
Electricity price (R/kWh)	0.54	R 152.44	155.388	2%	158.34	4%	161.293	6%
Density: Whole-stick sugarcane with residue (kg/m^3)	320	R 152.44	152.301	0%	152.301	0%	152.301	0%
Speed: Infield transport (km/h)	10	R 152.44	151.348	-1%	150.451	-1%	150.051	-2%
Speed: Road transport (km/h)	60	R 152.44	152.032	0%	151.844	0%	151.368	-1%
Distance: Field to processing plant (km)	20	R 152.44	153.38	1%	150.05	-2%	150.751	-1%
Distance: Processing plant to mill (km)	25	R 152.44	152.44	0%	152.429	0%	152.432	0%
Operating hours: Infield transport (h)	10	R 152.44	R 151.32	-1%	R 150.58	-1%	R 150.12	-2%
Operating hours: Forage harvester (h)	10	R 152.44	152.147	0%	151.965	0%	151.902	0%
Operating hours: TOP plant (h)	24	R 152.44						
% Residue left infield for agronomy (%)	50	R 152.44	147.009	-4%	141.518	-7%	136.113	-11%
Recovery efficiency: Forage harvester (%)	66	R 152.44	157.894	4%	163.259	7%	163.651	7%
Residue bulk density: Forage harvester (kg/m^3)	65	R 152.44	151.717	0%	151.236	-1%	150.796	-1%
License and Insurance (% purchase price) (Forage harvester)	4 693	R 152.44	152.445	0%	152.454	0%	152.464	0%
Maintenance % (Forage harvester)	80	R 152.44	153.152	0%	153.87			
Max life (yr) (Forage harvester)	15	R 152.44	152.435	0%	152.435	0%	152.435	0%
Resale: Base % (Forage harvester)	35	R 152.44	152.132	0%	151.829	0%	151.526	-1%
Resale: Base age (yr) (Forage harvester)	5	R 152.44	152.219	0%	152.003	0%	151.786	0%
Resale: Yearly % (Forage harvester)	5	R 152.44	152.264	0%	152.093	0%	151.923	0%
Resale: Minimum price % (Forage harvester)	10	R 152.44	152.435	0%	152.435	0%	152.435	0%
Weight loss: TOP (%)	30	R 152.44	152.066	0%	151.399	-1%	151.03	-1%
Biomass bulk density: TOP (kg/m^3)	800	R 152.44	152.435	0%	152.435	0%	152.435	0%
License and Insurance (% purchase price) (TOP plant)	21 689	R 152.44	152.457	0%	152.478	0%	152.5	0%
Maintenance % (TOP plant)	5	R 152.44	152.449	0%	152.464	0%	152.478	0%
Max life (yr) (TOP plant)	15	R 152.44	152.424	0%	152.415	0%	152.41	0%
% downtime per year (TOP plant)	6	R 152.44	152.435	0%	152.435	0%	152.435	0%
Resale: Base % (TOP plant)	0	R 152.44	152.435	0%	152.435	0%	152.461	0%
Resale: Base age (yr) (TOP plant)	0	R 152.44	152.435	0%	152.435	0%	152.435	0%
Resale: Yearly % (TOP plant)	0	R 152.44	152.435	0%	152.435	0%	152.435	0%
Resale: Minimum price % (TOP plant)	10	R 152.44	152.448	0%	152.461	0%	152.474	0%

12. APPENDIX D: CASE STUDY OUTPUTS

Appendix D contains the residue recovery route cost breakdowns for the two case studies conducted in Chapter 0.

12.1 Noodsberg Mill Area

Table 12.1 Model output costs: Harvesting operation for Noodsberg case

	Sugarcane Harvesting Cost (R/t of sugarcane)				
	Manual (Stack) Harvesting		Chopper Harvester		
	Green (No separation)	Green (Separation)	Green (No separation)	Green (Partial separation)	Green (Separation)
Total	R 87.98	R 89.60	R 94.05	R 90.66	R 83.05
Harvesting	R 25.10	R 39.23	R 38.15	R 37.10	R 36.32
Loading infield	R 8.80	R 8.16	-	-	-
Infield transport	R 12.03	R 11.26	R 20.43	R 19.55	R 17.02
Transloading	R 7.11	R 6.60	R 8.68	R 8.31	R 8.04
Road transport	R 34.92	R 24.35	R 26.79	R 25.70	R 21.67

Table 12.2 Model output costs: Sugarcane residue recovery operation for Noodsberg case

	Residue Collection Cost (R/t of sugarcane residue)					
	Baling		Forage Harvester		Silage Wagon	
Distance	20 km	25 km	20 km	25 km	20 km	25 km
Total	R 355.19	R 362.52	R 309.31	R 326.94	R 430.23	R 436.45
Rake operation	R 40.67	R 40.67	R 43.14	R 43.14	R 40.67	R 40.67
Residue collection	R 210.92	R 210.92	R 148.84	R 148.84	R 354.29	R 354.29
Twine cost	R 12.00	R 12.00	-	-	-	-
Loading infield	R 10.08	R 10.08	-	-	-	-
Infield transport	R 32.05	R 32.05	R 43.83	R 43.83	-	-
Transloading	R 8.54	R 8.54	R 8.64	R 8.64	R 8.54	R 8.54
Road transport	R 40.93	R 48.26	R 64.86	R 82.49	R 26.73	R 32.95

Table 12.3 Model output costs: Sugarcane residue processing operation for Noodsberg case

	Residue Processing Cost (R/t of processed sugarcane residue)		
	Torrefaction	Pelleting	TOP
Distance (km)	25	25	25
Total	R 341.69	R 340.92	R 452.94
Residue processing	R 316.90	R 316.74	R 427.95
Loading	R 10.00	R 11.00	R 10.07
Road transport	R 14.77	R 15.52	R 14.92

12.2 Hypothetical Large-scale Grower

Table 12.4 Model output costs: Harvesting operation for large-scale grower case

		Sugarcane Harvesting Cost (R/t of sugarcane)				
		Manual (Stack) Harvesting		Chopper Harvester		
		Green (No separation)	Green (Separation)	Green (No separation)	Green (Partial separation)	Green (Separation)
Total		R 246.29	R 198.11	R 205.41	R 197.27	R 172.65
	Harvesting	R 25.25	R 39.42	R 31.73	R 30.88	R 30.25
	Loading infield	R 9.21	R 8.51	-	-	-
	Infield transport	R 12.68	R 11.88	R 20.73	R 19.89	R 17.27
	Transloading	R 7.49	R 6.76	R 8.88	R 8.52	R 8.25
	Road transport	R 191.66	R 131.54	R 144.07	R 137.98	R 116.88

Table 12.5 Model output costs: Residue recovery operation for large-scale grower case

		Residue Collection Cost (R/t of sugarcane residue)					
		Baling		Forage Harvester		Silage Wagon	
Distance		5 km	153 km	5 km	153 km	5 km	153 km
Total		R 308.57	R 554.85	R 233.40	R 687.68	R 394.93	R 673.20
	Rake operation	R 35.58	R 35.58	R 37.74	R 37.74	R 35.58	R 35.58
	Residue collection	R 176.86	R 176.86	R 124.66	R 124.66	R 359.35	R 359.35
	Twine cost	R 12.00	R 12.00	-	-	-	-
	Loading infield	R 12.37	R 12.37	-	-	-	-
	Infield transport	R 36.25	R 36.25	R 46.62	R 46.62	-	-
	Transloading	R 12.37	R 12.37	R 9.74	R 9.74	-	R 20.96
	Road transport	R 23.14	R 269.42	R 14.64	R 468.92	-	R 257.31

Table 12.6 Model output costs: Residue processing operation for large-scale grower case

		Residue Processing Cost (R/t of processed sugarcane residue)		
		Torrefaction	Pelleting	TOP
Distance (km)		153	153	153
Total		R 146.69	R 146.91	R 173.43
	Residue processing	R 102.70	R 92.01	R 129.02
	Loading	R 16.00	R 16.00	R 16.33
	Road transport	R 27.97	R 39.57	R 28.08