MODELLING SUGARCANE QUALITY IN THE CONTEXT OF MILL SCALE SUPPLY CHAIN LOGISTICS

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ABSTRACT

The length of milling season (LOMS) refers to the length and timing of sugarcane crushing operations at a sugar mill. LOMS is central to the competitiveness and profitability of any sugar mill supply area (MSA). Conflicting interests between supply chain stakeholders can make adjusting the LOMS difficult. The LOMS should take into account weather conditions, cane quality, milling capacity, supply chain capabilities and other interrelated issues, such as agronomics. Previous LOMS models in South Africa were developed over a decade ago and there was scope to improve the calculation of risks by using a stochastic modelling approach. Recently, a stochastic model named LOMZI was developed to evaluate stockpiling options at Umfolozi. In this study, LOMZI was adapted and expanded to allow the LOMS for any MSA in South Africa to be investigated. However, mill area specific applications of the updated model fell outside the scope of this study. As it currently stands, LOMZI simulates a sugarcane supply chain from the point where sugarcane is cut, up to delivery at the mill. During the process of adapting LOMZI, the simulation of sugarcane quality was identified as an important area for improvement in the model and this became the focus of the study. A predictive MSA scale cane quality model was developed, based on recent weather conditions and a mechanistic understanding of sugarcane quality. The quality model was developed to simulate the daily average brix %, pol % and fibre % of sugarcane delivered to the mill. The preceding 11 weeks' rainfall and temperature values were used to predict cane quality. A total of 98 mill-specific coefficients were calibrated from historic milling data and, for model demonstration purposes, the quality model was applied at two mills, namely Sezela and Umfolozi. Independent verifications yielded R^2 values between 0.56 and 0.74. A useful method to estimate the average burn/cut to crush delay for a MSA was also identified. The quality model has been successfully integrated with LOMZI. Future work is envisaged to expand LOMZI and to model the operations of sugar mills and the RV cane payment system.

PREFACE

I, Edwin Peter Garland Jenkins, declare that:

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

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

Signed: ....

C. N. Bezuidenhout

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

Signed: ....

G. Ortmann

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1. INTRODUCTION

On average, the South African sugar industry harvests 18.8 million tons of sugarcane and produces 2.3 million tons of sugar each year (SASA, 2014). Apart from producing sugar and molasses, the industry also produces several other downstream products, such as ethanol and furfural. It has been estimated that over a million people depend on the South African sugar industry for their livelihoods (SASA, 2014). The South African sugar industry underwent a period of de-regulation in the 1990's (Moor and Wynne, 2001) and income is based on global sugar prices, which means that the industry competes at a global level. Rising input costs, especially fuel and fertilizer, and increased global sugar supply have reduced the international competitiveness of many sugar-producing regions (Higgins *et al.*, 2004). Thus, maintaining the competitiveness and efficiency of South African sugar mills is of great importance.

The length of milling season (LOMS) refers to the length and timing of sugarcane crushing operations at a sugar mill. The correct LOMS can increase the productivity and profitability of a sugar milling area (Muchow *et al.*, 1998a; di Bella *et al.*, 2008). Milling seasons vary widely, depending on country and region (Hildebrand, 1998; Moor and Wynne, 2001). For example, the milling season in Louisiana (United States) is relatively short and comprises 14 weeks. In contrast, there is no milling season in Columbia and cane is crushed the whole year round (Hildebrand, 1998). Grunow *et al.* (2007) describe a mill and refinery in Venezuela with a milling season from October to May. Imported raw sugar is then processed during the off-season. Higgins and Muchow (2003) state that the harvest season in Australia is from early winter to late spring and is carried out over several months because of limits to the capacity of mills and transportation. In South Africa, the harvesting season is relatively lengthy at between 30 to 38 weeks, running from April until December (Moor and Wynne, 2001; Bezuidenhout and Singels, 2007).

Whenever the LOMS is discussed, it is likely to raise conflicting arguments (van der Pol, 1987; Muchow *et al*., 1998a; Wayne and Groom, 2003), especially in South Africa, where the milling and growing segments of the supply chain are often separately owned (Hildebrand, 1998). The LOMS must be such that it balances the needs of the grower and the miller, while concurrently ensuring the continued international competitiveness of the sugar industry (Hildebrand, 1998). For these reasons, the sugar supply chain should be evaluated as a single entity, to ensure continued competitiveness and profitability when determining the LOMS (Hildebrand, 1998; Gaucher *et al.*, 2004; Lejars *et al.*, 2008).

Computer modelling has been used before to help improve the operation of sugarcane supply chains (Barnes *et al.*, 2000; Zhaorong *et al.*, 2005; Rangel *et al.*, 2010; Boote, 2012). While the South African sugar industry was undergoing deregulation, the South African Cane Growers' Association developed an economic model to facilitate the determination of an optimal harvest season for a mill area (Hildebrand, 1998; Moor and Wynne, 2001). Named the LOMS Model, it was run for all but three of South Africa's 15 mills. The optimal LOMS for the individual mills ranged between 34 and 38 weeks (Moor and Wynne, 2001). Results from the LOMS Model provided an objective starting point for growers and millers to negotiate a milling season length for many of the mills in South Africa (Wynne and Groom, 2003).

The LOMS Model was based on linear programming principles. Hildebrand (1998) stated that the approach was to maximise profits from sugar by optimising the season length for a specific mill area, while taking into account the proceeds sharing arrangements. This seems to contradict the suggestion that growers and millers should be viewed as a single business entity when LOMS is under evaluation. In the LOMS Model, the length of the season was determined by dividing the total sugarcane to be crushed by the throughput capacity of the sugar mill. The LOMS Model took into account historical crop performance, mill utilisation, agronomic and harvesting factors, as well as the relevant costs and incomes (Hildebrand, 1998). The optimal season length, in weeks, was reached when marginal losses from declining cane quality were greater than the benefits of increased capacity utilisation (Wynne and Groom, 2003).

The LOMS Model was developed over a decade ago and ignored some of the complexities involved in the sugarcane supply chain. The model was based on average cane quality and ignored variability. It was developed before the recoverable value (RV) cane payment system was implemented and also excludes rainfall, which could interrupt the supply chain. It is possible that under certain assumptions the model's recommendations do not hold true and there is scope to review the modelling of the LOMS to include a wider range of variables, risks and uncertainties. Stochastic modelling improves the calculation of risk, compared to other modelling approaches. Boote (2012) developed a stochastic model called LOMZI, to examine stockpiling options at Umfolozi. There was scope to adapt LOMZI into a modelling framework that could help evaluate LOMS for any mill supply area (MSA).

The quality of cane delivered to a sugar mill is of utmost importance, as it influences sugar production and profitability (Le Gal *et al.,* 2008). Seasonal weather patterns have a large influence on sucrose content and accumulation in sugarcane (Inman-Bamber, 1994a; Singels *et al.,* 2012). The impact of harvest season length on overall cane quality has also been thoroughly covered in the literature (Higgins and Muchow, 2003; Wynne and Groom, 2003; Wynne *et al.,* 2009). Sugarcane quality peaks during the cooler, drier months of the year and the longer the milling season, the lower the average quality of sugarcane. If determining the length of milling season was a simple matter of maximising the quality of sugarcane processed, the season would have to fit into two weeks (Grunow *et al.,* 2007). However, cane quality must be balanced against many other factors to maximise supply chain profitability, such as the cost of harvesting equipment. Sugarcane quality modelling was identified as an area for improvement in LOMZI, which became the focus of this study.

Thus, the aim of this study was to develop a predictive mill supply area scale cane quality model, based on recent weather conditions and a mechanistic understanding of sugarcane quality, in a logistical context. This model was to be incorporated into an adapted LOMZI modelling framework.

Specific objectives of the study were to:

a) review the scientific literature to determine the factors that affect the LOMS in a typical milling area,

b) develop, calibrate and verify a sugarcane quality model to predict the average daily quality of cane delivered to a sugar mill. The quality model must be integrated within the LOMZI stochastic modelling approach,

c) refine the LOMZI Model to allow for easier calibration and application at any mill supply area (MSA). The adjusted model must account for the flow of sugarcane from the field to the mill for a specific mill area to help evaluate the LOMS, and,

d) identify areas for possible future research regarding the quality model and LOMZI.

A thorough calibration of LOMZI for an individual mill area was not in the scope of this study. Rather, the objective was to define a more generic modelling tool that could be calibrated for any milling area in South Africa.

A literature overview of factors that influence the LOMS is presented in Chapter 2. Because the development of a sugarcane quality model became the focus of this study, it is presented before a description of LOMZI. Chapters 3 and 4 provide the methodology, results and discussion of the sugarcane quality model. Chapter 5 describes how the LOMZI Model has been adapted to allow for applications at any MSA. A description of how the quality model has been incorporated into LOMZI is also included. Finally, conclusions and possible issues for future research are presented in Chapter 6.

2. AN OVERVIEW OF FACTORS THAT AFFECT THE LENGTH OF MILLING SEASON

The local circumstances which affect the LOMS are weather conditions, agronomic practices, economic factors, industry structures, policy and legislation set by government and the politics between growers and millers. Historical norms often play a large role in determining the LOMS (Hildebrand, 1998; Moor and Wynne, 2001). The length of the milling season depends on the amount of sugarcane that needs to be processed for a particular area and the capacity of the sugar mill (Hildebrand, 1998).

The start and length of the harvest season impacts on seasonal cane quality, recoverable value and the growth and yield of the following ratoons (Muchow *et al.*, 1998b). Milling profitability depends on these factors, as they determine the use of capital assets, maintenance schedules, labour planning, rate of crushing, recovery of sugar and financial planning. When and how much sugar will be produced also impacts on marketing strategies and the maximisation of earnings from sugar exports (Muchow *et al.*, 1998b).

This chapter comprises short literature overviews of the factors that affect the length of milling season. In terms of scope, the literature review does not focus on in-field agronomics. The focus is rather on how the operating environment, sugarcane quality, harvesting, transport and milling of the crop interact and impact the LOMS. Although a high degree of connectivity exists, factors are broadly separated into: (a) the operating environment, (b) seasonal effects on the crop, (c) harvesting issues, (d) transport issues, and (e) mill throughput and production.

2.1 The Operating Environment

The operating environment can be defined as the conditions, entities, events and factors surrounding an organisation that influence its activities, choices, risks and opportunities (Business Dictionary, 2013). Some of the operating environment factors that influence the length of the milling season are: (a) mill and farm ownership regimes, (b) industry rules and configuration, and (c) payment and incentive systems.

2.1.1 Ownership and politics

Greater complexity is added to determining acceptable milling season lengths when the milling and growing segments of the industry are owned separately (Hildebrand, 1998). The nature of the South African sugar supply chain implies that often growers and millers approach the LOMS from different perspectives. On the one hand, growers would prefer to harvest the majority of their sugarcane when the crop is fully mature, with a high sucrose content, and when fields are dry and accessible (Hildebrand, 1998; Stray *et al.,* 2012). On the other hand, the miller, who has considerable fixed costs in the mill, aims to spread the milling operation out over a longer period of time (Hildebrand, 1998; Stray *et al.,* 2012). A longer season reduces the capacity required to cope with the annual crop and reduces the time during which the mill stands idle in the off-season.

Implementing changes to the milling season's timing and length are more difficult when the number of stakeholders is increased. Historical norms and the political strength of either growers or millers may be the reason why such vastly different milling season lengths can be observed around the world (Hildebrand, 1998). Milling season adjustments can often only be made after negotiations between the growers and millers have taken place (Hildebrand, 1998; Todd *et al.,* 2004). A mutually beneficial length of milling season must be negotiated between growers and millers. The arrangement must enable the survival of both parties, but also ensure the competitiveness of the mill area as a whole (Hildebrand, 1998). A good relationship between all supply chain stake-holders is essential, if any measure of success is to be achieved (Muchow *et al.,* 1998b)

2.1.2 Cane payment systems and the LOMS

Cane payment systems can change stakeholders' perceptions about an acceptable milling season length. There are also links between cane payment systems and incentives to improve cane quality or to expand production (Todd *et al.,* 2004).

Cane payment systems can be divided into either fixed cane price, fixed revenue sharing or variable revenue sharing systems (Todd *et al.,* 2004). A fixed price system is where growers are paid for the tons of sugarcane delivered to the mill. Fixed revenue sharing means that proceeds are shared between growers and millers at a fixed percentage. A fixed revenue system is used in South Africa (Hildebrand, 1998). A more sophisticated system is variable revenue sharing. Under this system, any proceeds from cane quality, above a certain benchmark, benefit the grower. Alternatively, any improvement in sucrose recovery, above a certain benchmark, benefits the miller. The complexity of variable payment systems makes them harder to administer, but offer incentives to improve cane quality and factory efficiency (Todd *et al.*, 2004).

To encourage an improvement in sugarcane quality delivered to sugar mills, the recoverable value (RV) payment system was adopted in the South African sugar industry in 2000 (Wynne, 2001). The RV formula is used to link the farmer's payment to cane quality including, the sucrose, non-sucrose and fibre levels. This payment system averages out the seasonal change of sugar content (see Section 2.2.1), so that there is no direct incentive to deliver cane when sucrose content is at its peak (Wynne *et al.*, 2009; Stray *et al.*, 2012). This is referred to as relative cane payment.

A disadvantage of relative cane payment systems is that they have the potential to disguise the effects of a sharp drop-off in cane quality at the start and end of the milling season. This can lead to an unacceptable drop in the season average sugar content (Wynne *et al.*, 2009).

2.1.3 The role of the Mill Group Boards

At South African sugar mills, the committees responsible for administering cane supply are known as Mill Group Boards (MGBs). This committee comprises grower and miller representatives and the chairmanship alternates annually between the two parties. MGBs are legislated and must set the starting date and length of the milling season, based on estimates of the size of the crop to be crushed and the rate at which the mill can operate (Hildebrand, 1998; Gaucher *et al.*, 2004; Schorn *et al.*, 2005). MGBs are responsible for season planning and ensuring a reliable supply of cane to the mill. The aim is to utilise the mill's crushing capacity, while maximising the recoverable value throughout the season (Le Gal *et al.*, 2008).

MGBs are required to make an informed decision about the size of the sugarcane crop to be processed by using field estimates provided by growers, the scouting of fields by mill employees and forecasts from crop models (de Lange and Singels, 2003). MGBs across the sugar industry apply different methods to predict the size of the crop. Bezuidenhout and Singels (2007) indicate that some of the methods used by MGBs tend to be more subjective, while others are more scientific.

The MGB allocates daily or weekly rateable deliveries to each grower, based on the grower's crop estimate. This system is meant to aid the grower in making deliveries, but can lead to supply issues, as many growers are unable to meet their targets (Wynne, 2001). After comparing several seasons' worth of data from the Sezela Mill, Le Gal *et al.* (2004) noted that failure to meet daily rateable deliveries (DRDs) occurred more frequently at the start and end of the milling season. It took roughly three weeks for growers to reach their DRDs at the start of the season. After DRDs are reached the supply remains fairly constant until it begins to taper off during the last few of weeks of the season.

2.2 The Crop as affected by the Season

The most important crop issues that play a role in the milling season are cane quantity and cane quality. The impacts that seasonal weather conditions have on sugarcane production are well documented. In South Africa, sugarcane is grown under widely varying climatic conditions (Bezuidenhout and Gers, 2002; Bezuidenhout and Singels 2007). The South African sugar milling areas are also at the mercy of weather events, such as tropical cyclones and frequent droughts (Bezuidenhout and Singels, 2007).

2.2.1 Sugarcane quality

The sucrose content, non-sucrose content and fibre content of sugarcane delivered to the mill, and hence RV, follow seasonal patterns (Wynne *et al.*, 2009). In South Africa, RV is low at the beginning of the harvest season and gradually rises to a peak. The peak occurs when quality is highest i.e. maximum sugar yield and low fibre content. When this peak occurs depends on the geographical location, weather conditions, the variety of the cane and its age (Glover, 1971; Inman-Bamber, 1994a; Higgins *et al.*, 1998; Le Gal *et al.*, 2004). After the peak, RV remains fairly constant until spring, when rainfall causes a sharp drop in cane quality (Grunow *et al.*, 2007). Le Gal *et al.* (2004) and Stray *et al.* (2012) argue that the recoverable value of sugarcane follows a bell-shaped curve.

Muchow *et al.* (1998a) state that the optimisation of harvest dates can improve productivity and profitability. These improvements can at times be achieved without any further investment in harvesting or milling equipment, but vary widely across mill areas and seasons (Higgins and Muchow, 2003). Extensive research has been carried out on the optimisation of harvest dates to take into account the seasonal and geographical variation in the sucrose content and the quality of sugarcane, in order to increase profitability (Higgins *et al.*, 1998; Muchow *et al.*, 1998a; Higgins and Muchow, 2003; Le Gal *et al.*, 2004; Zhaorong, 2005).

Season average sucrose content tends to decrease as season length is increased. This is because more of the milling takes place when sucrose levels are low at the beginning and end of the season (Moor and Wynne, 2001; Todd *et al.*, 2004). Figure 2.1 illustrates the theoretical difference in season average sucrose content for different season lengths for a typical sucrose percent curve.

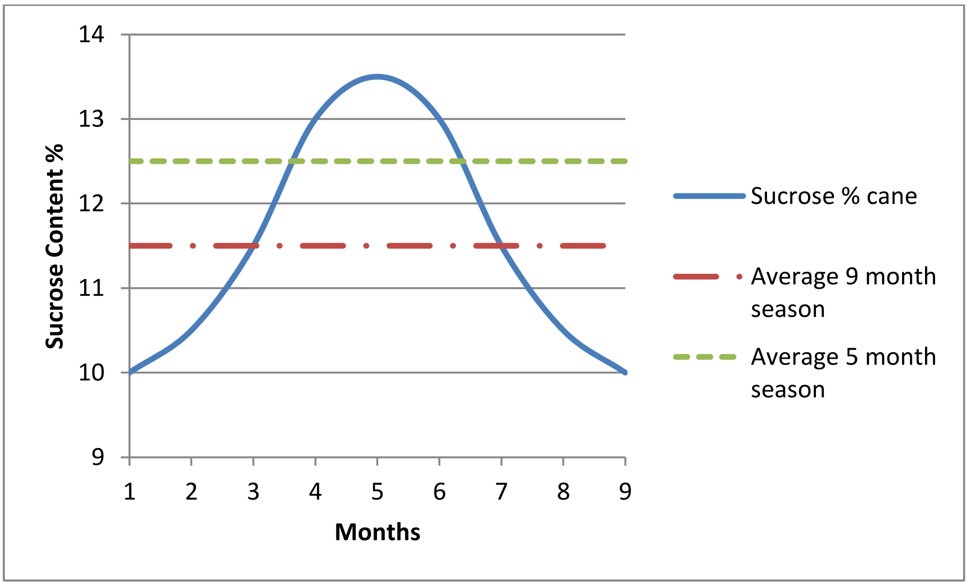


Figure 2.1 A stylized version of a sucrose curve and seasonal average sucrose contents for different milling season lengths (Todd *et al.*, 2004)

Todd *et al.* (2004) note that even if a relative cane payment system is used, the length of the milling season is still a contentious issue. This is because the average sucrose content is taken into account, when distributing revenue between growers and millers.

Mill area recoverable value curves are different each year, depending on weather conditions. For each mill area, it is possible to produce a representative sucrose curve for all the weeks of the year, using historical data (Moor and Wynne, 2001). Le Gal *et al*. (2004) noted general trends in cane quality over several seasons for a particular mill area, but greater inter-annual variability in RV at the start and end of the season. Figure 2.2 shows typical seasonal and regional variations in RV for a mill area.

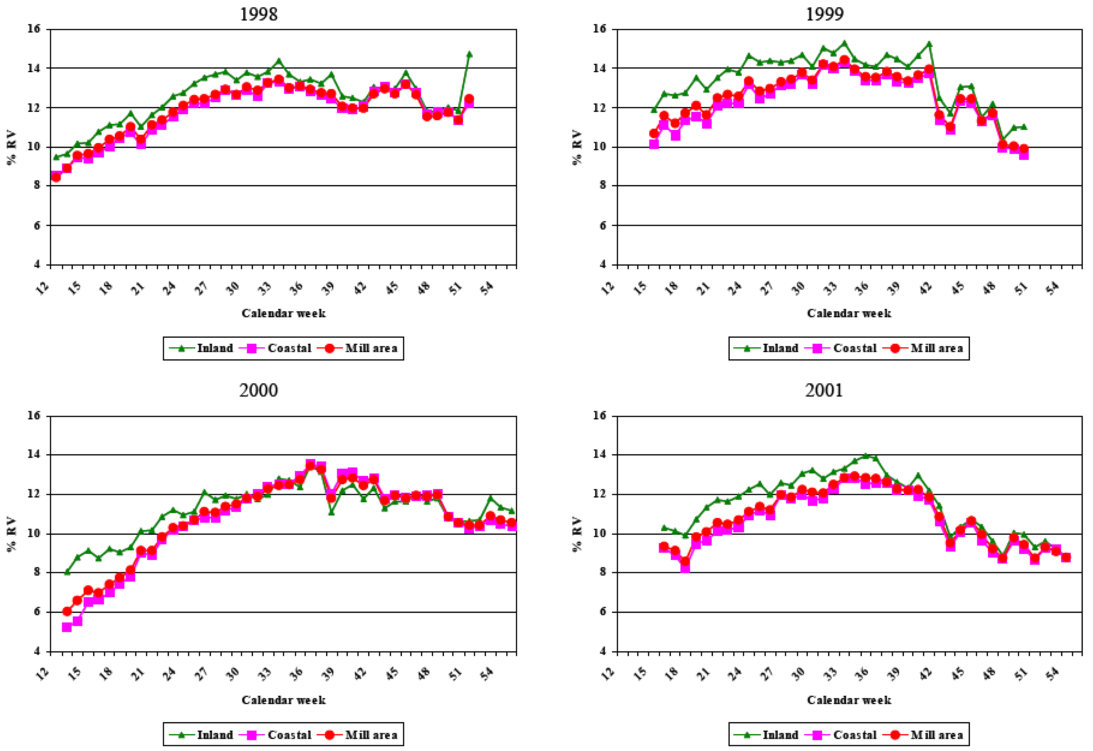


Figure 2.2 Recoverable Value curves for the Sezela Mill area, 1998-2001 (Le Gal *et al.*, 2004)

Rainfall has a significant impact on the optimal harvesting season for sugarcane. Sufficient, well-distributed rainfall is needed during the summer months to allow the proper growth of the sugarcane crop. As the sugarcane reaches maturity, a lower availability of water is desirable to allow the cane to ripen (Singels *et al.*, 2000). High amounts of rainfall during the harvest season promote growth and reduce sugar recovery (Higgins and Muchow, 2003).

2.2.2 Models of sugarcane quality

Accurate quality prediction is of considerable interest and use to sugarcane growers and millers. It is especially important when a relative cane payment system is used, because it can help determine accurate payments to growers throughout the season (Singels *et al.,* 2012). Cane quality prediction can help millers make decisions about mill operations, scheduling and maintenance, and can even help in the marketing of sugar (Bezuidenhout and Singels, 2007). Sugarcane quality models can be either point based crop models, or models that predict quality at a larger, and often a mill area, scale.

Methods to predict sugarcane quality are not new to the South African sugar industry. Earlier methods seem to focus on regression type models, often at a large spatial scale. Brown (1973) found strong correlations between the amount of rainfall recorded between February and May and season sucrose % cane in South Africa, but no attempt was made to use this as a model of cane quality and it remained an observation. Hoekstra and Baker (1977) discussed two methods used to predict season average pol % cane. The first method was to predict pol % cane before the season, based on weighted averages from previous seasons. The second was a tool for predicting quality within a milling season, using the pre-season estimate and up-to-date pol % cane averages that occurred during the season. For each month of the season, different weightings, determined for each mill, were used. Taking the historic rainfall into account in the model did not do much to improve its predictive capacity and no mention was made of the model's performance. Glover (1971) used rainfall and minimum temperature to model the ripening of sugarcane. This was based on strong correlations between rainfall and temperature values and the sucrose % of cane for three sites in South Africa. Glover (1971) makes mention of the usefulness of quality predictions throughout the season, particularly to the miller.

More recently, several point based crop growth models have been developed. The South African Sugar Research Institute (SASRI) developed CANEGRO (Inman-Bamber, 1991; Singels and Bezuidenhout, 2002). CANEGRO is a detailed model used for research and it requires a high level of scientific expertise to operate. The model is a daily time step, point based model that simulates photosynthesis, canopy development and the distribution of resources within the sugarcane. CANEGRO also takes into account the soil water profile.

CANEGRO and other models used to account for soil and climatic variables, were incorporated into the CANESIM Model by scientists at SASRI, to aid decision-making and research (van den Berg and Smith, 2005). CANESIM has formed the basis of many other decision support tools developed by SASRI. The model is mainly driven by water and needs daily rainfall, temperature, evaporative demand and the water-holding capacity of the soil as inputs (van den Berg and Smith, 2005). Yield is determined by the modelling of transpiration.

An Australian model, APSIM-Sugarcane, was developed by a large team of scientists and programmers from the Agricultural Production Systems Research Unit (APSRU) in Queensland (Keating *et al.*, 1999; O'Leary, 2000). The model was developed as a result of dissatisfaction with certain aspects of a previously developed model, AUSCANE (Wegener *et al.*, 1988). APSIM-Sugarcane simulates the radiation use and transpiration efficiency of sugarcane at a daily time step. Daily biomass accumulation is partitioned between the various components of the plant at fixed rates for different phonological stages of the plant. Daily photosynthate, partitioned to the stalk, is partitioned further to stalk sucrose after the stalk reaches a certain size. Sucrose partitioning is increased by stress factors relating to water, temperature and nitrogen. Cultivar differences are accounted for in the model. A unique feature of APSIM-Sugarcane is that the stalk water content is also simulated (O'Leary, 2000). APSIM-Sugarcane and CANEGRO are widely used around the world.

Another Australian model, QCANE, was developed in Queensland by the Bureau of Sugar Experiment Stations (Liu and Kingston, 1994). QCANE operates on a daily time step and is similar in form to APSIM-Sugarcane and CANEGRO, but has some differences (O'Leary, 2000). It has not been widely used. Marin and Jones (2014) developed a model similar to CANEGRO and APSIM-Sugarcane, using data specific to the conditions in Southern Brazil. The daily time-step model simulates biomass, sucrose concentration and other variables. It takes into account the soil water profile, daily weather and irrigation (Marin and Jones, 2014). In terms of performance, the model compared favourably with existing models.

Recently, Singels *et al.* (2012) compared a method at a supply-chain scale, which was employed by the RV Forecasting Committee of the South African Sugar Association to predict RV during the milling season, as well as two alternate methods, based on up-to-date RV values and forecasted agro-climatic conditions. The quality prediction method employed by the RV Forecasting Committee uses the previous five seasons' data for each mill. Smoothed, long-term averages of quality are used to predict RV during a season (Singels *et al.,* 2012). The first of the two other RV forecasting methods presented in Singels *et al.* (2012) is simply based on the difference between the current RV level and the long-term average to date RV level, and is referred to as TDRV1. The second RV forecasting method, referred to as TDRV2, uses recent and predicted agro-climatic conditions, as well as the current RV, to make a forecast of quality. The method used to take into account climatic conditions in TDRV2 is derived from CANESIM (Singels *et al.*, 2012; Bezuidenhout and Singels, 2007).

2.2.3 Reduction of optimal growing periods

The further the milling season stretches into the summer months, the less growing time is available for sugarcane to grow with a full canopy under optimal conditions. This has an influence on yields of the subsequent ratoons (Hildebrand, 1998; Moor and Wynne, 2001; Donaldson *et al.,* 2008; Donaldson *et al.*, 2011).

Crops harvested in December have a lower biomass yield than crops harvested in autumn and winter. The main reason is the lower radiation use efficiency in the December crops, most likely due to premature ripening during winter and a slow recovery from this effect (Donaldson *et al.,* 2008; Donaldson *et al.*, 2011).

2.2.4 Crop estimate

An accurate estimate of crop size allows for the efficient milling of the crop and is used to determine the start and end dates of the milling season (de Lange and Singels, 2003; Weekes, 2004). Crop size is primarily a function of the area under sugarcane and the climatic conditions experienced over a season. The nature of crop estimation is that uncontrollable factors, such as climatic variability, lead to inaccuracies in predictions. It is important to be able to predict the level of error or be able to calculate the risk associated with a particular estimate (Bezuidenhout and Singels, 2007).

Crop forecasting is most often approached by using statistical and sampling techniques (Stephens and Middleton, 2002; cited by Bezuidenhout and Singels, 2007). However, Lumsden *et al.* (1998) and Bezuidenhout and Singels (2007) demonstrate the effectiveness of using a sugarcane yield model and climatic forecasts to provide an estimate of crop size at a mill area scale. An accurate prediction of climatic factors, among others, is needed for this approach to be effective.

Crop estimates can be divided into vertical and horizontal components. Vertical refers to the yield per area and horizontal refers to area under cultivation. Vertical performance is dependent on climatic variability and this cannot be controlled by growers, but horizontal performance can be (Wynne, 2001).

2.3 Harvesting

Wiense and Reid (1997) state that the harvesting practices in South Africa have evolved to an optimum point over many years. Harvesting in South Africa is mainly manual and a small percentage is mechanised. Fields are often burnt before cutting, to defoliate the cane, which makes harvesting easier. Harvesting can be fully manual, where cutting and loading is by hand, semi-mechanised, where cutting is manual and loading is mechanical, or fully mechanised, where cutting and loading is combined in a single operation, by using sugarcane harvesters (Rangel *et al.*, 2010).

Decisions that growers make about harvest capacity affect mill efficiency (Gaucher *et al.*, 2004). The harvesting factors that will be discussed in the following subsections are: (a) delays caused by rainfall, (b) difficulties caused by wind, (c) disruptions due to frost, (d) labour issues, and (e) cane deterioration.

2.3.1 Rainfall and harvest delays

Weather conditions determine how many days are available for harvesting (Higgins and Davies, 2005; Rangel *et al.*, 2010; Kadwa, 2012). Besides reducing the recoverable value, spring and summer rainfall cause disruptions in the supply of sugarcane to mills in South Africa (Boote *et al.*, 2011). Rainfall leads to harvesting difficulties, increased burn to crush delays, damage to fields, as well as increased ash percentages (Donaldson, 1998; Hildebrand, 1998; Kadwa, 2012). Rainfall can also make burning cane fields for harvesting difficult or impossible (Weekes, 2004). Accurate weather forecasts improve optimisation efforts, because these aid in planning for possible disruptions in cane supply, due to bad weather (Higgins and Muchow, 2003).

Boote (2012) and Kadwa (2012) assumed a relationship between the depth of rainfall and the duration of harvest delays for the Umfolozi and Eston Mills, respectively, as shown in Table 2.1. It is likely that the relationship between rainfall depth and harvesting delays will be different for each mill area, depending on local conditions.

Table 2.1 Harvesting days lost for different rainfall depths at Eston (Kadwa, 2012) and Umfolozi (Boote, 2012)

Rainfall depth (per day)	Umfolozi	Eston
> 5 mm	1 day	2 days
> 10 mm	2 days	3 days
> 30 mm	3 or more days	4 days
> 50 mm		5 days

There is a compound effect of extending the milling season into the rainy season. Higher chances of rainfall can interrupt harvesting and milling operations, thus prolonging the milling season even further (Boote, 2012; Kadwa, 2012).

2.3.2 Wind and harvest difficulties

Windy conditions can have an effect on the degree of lodging of sugarcane. Lodged sugarcane experiences reduced growth rates (Stray *et al.*, 2012) and it is difficult to harvest (James, 2004).

Windy conditions can also delay cane burning before harvesting, as there is an increased risk of uncontrollable or runaway fires (Weekes, 2004). Avoiding wind is one of the reasons why burning is usually performed early in the morning. These delays can potentially extend the milling season by disrupting harvesting.

2.3.3 Frost and harvest disruptions

In Louisiana, the milling season is kept to approximately three months because of the risk of winter frosts (Eggleston *et al.,* 2004). In South Africa, frost can affect inland, higher altitude cane growing areas in the KwaZulu-Natal midlands. Between one-fourth and one-third of the sugarcane grown in the midlands can be affected by frost every season (de Haas, 1981). The lower the temperature experienced, the greater the damage to sugarcane. Temperature and damage relationships vary with cane variety and crop cover (Irvine, 2004).

The biggest impact that frost has on cane quality is the formation of dextran in damaged internodes (Mann, 1991; Eggleston *et al.*, 2004; Irvine, 2004). Cane that has been completely frozen may be unsuitable for sucrose crystallization three weeks after the frost occurred. In less severe cases, there may only be a reduction in sucrose yield several months after the cane was frosted. Economic losses can be minimised by harvesting severely frosted cane soon after the freeze occurs (Irvine, 2004). Mann (1991) suggests that the drop in cane quality observed at some sugar mills, after widespread frosting, may be due to cutting immature cane which has not been properly topped, instead of the deterioration of sucrose.

Widespread frosting will disrupt a uniform cane supply, because large areas of damaged cane may need to be harvested as quickly as possible. This means that some farmers must deliver above their DRDs, while others may need to hold back.

2.3.4 Labour and harvesting

Shortages of cane cutters are becoming more common throughout the sugar industry in South Africa (Murray, 2008). In South Africa, the majority of sugarcane is cut manually and it is therefore important to consider labour issues when determining suitable milling season lengths. The majority of labour that is employed during the milling season is directly involved with the harvest operation.

Manual harvesting is hard physical work, usually performed under hot and unpleasant conditions (Christie *et al.,* 2008). It is not regarded as an ideal job and there is often low social status associated with cane cutting. Shortages of cutters occur as national levels of industrialisation increase and easier or better paid jobs become available (James, 2004; Kadwa, 2012).

Cutter productivity varies with trash percentage, stalk length and thickness, the degree of lodging, the presence or absence of weeds, crop yield per hectare, the suitability of the tools used, physique and age of the cutters, and the payment systems and financial aspirations of the labour (James, 2004). Meyer and Fenwick (2003) found that cane cutter performances were widely different between cutters, farms and regions and that the type of cutting system used has the biggest impact on cutter output.

The availability and reliability of cane cutters is an important factor to consider. Kadwa (2012) found that the absenteeism of cane cutters, especially after pay weekends, lengthened the milling season, due to reduced harvesting rates. Absenteeism after pay weekends was often greater than 50 per cent. After Christmas, the availability of cutters is generally low (Le Gal *et al.,* 2004) making the extension of the milling season beyond this date problematic.

Climatic conditions not only affect the ease of extracting cut sugarcane from the field, but can also affect the productivity of labour. On rainy days, there is often a high level of staff absenteeism. Temperature extremes make physical labour unpleasant. Most cane cutters begin work early in the morning, to avoid cutting during the midday heat (Christie *et al.,* 2008). Donaldson (1998) states that the feasibility of harvesting in summer months depends on labour availability and the discomfort of working in summer heat.

There is the possibility that it may become harder to find labour for cane cutting, due to factors such as debilitating diseases e.g. HIV/AIDS, or the strenuous nature of the job (Meyer and Fenwick, 2003). A shortage of cane cutters meant that growers in Mpumalanga were unable to meet their DRDs at the start of the 2006/2007 season (Murray, 2008).

A shortened milling season would result in higher DRDs, which means that growers would require more cutters over a shorter period to meet their deliveries. Employing more people for a shorter time would probably result in individual cutters earning less money per season (Le Gal *et al.,* 2004; Le Gal *et al.,* 2008).

Strikes and industrial action are factors which can potentially have a devastating effect on the length of sugar milling season and hence mill area profitability. The profitability of a sugar milling area will be severely affected if strikes occur when the recoverable value of the sugarcane is at its highest.

2.3.5 Cane deterioration

Sugarcane, like most other agricultural crops, starts to deteriorate immediately after burning and/or harvesting (Milan *et al.,* 2006). Enzymes that are naturally present in the cane stalks begin the deterioration process. Deterioration is worsened by other organisms that enter the sucrose-bearing tissues at a later stage. These organisms invert the sucrose, consume the glucose and form other products, including alcohols, acids and gums (Lionnet, 1996). Loading and transport should be arranged as soon after cutting as possible to minimise deterioration (Weekes, 2004). Road transport or tractor transport allows the shortest time between harvesting and crushing (Milan *et al.*, 2006).

Of the number of post-harvest deterioration products formed in sugarcane, Dextran polysaccharide has often been used as an indicator of the level of deterioration, because it is the cause of many of the problems experienced in a sugar factory, due to deteriorated sugarcane (Eggleston, 2002). There are other deterioration products that affect mill operation and these are often lumped under the term dextrans (Ravno and Purchase, 2005).

Dextrans in deteriorated cane reduce the quantity and quality of sugar produced (Morel du Boil and Wienese, 2002). High levels of dextrans cause an increase in viscosity, slow boiling rates, crystal deformation and an increase in the inversion of sucrose. This leads to a reduction in milling capacity and sugar recovery. This can increase the length of the harvest season and influences the amount of cane that must be carried over to the next season (Ravno and Purchase, 2005).

Ravno and Purchase (2005) conclude that dextran levels follow a predictable pattern over the harvest season. Dextran levels are high at the start of the season and drop to low levels during winter. When spring rains start, there is a sharp increase in dextran levels. Figure 2.3 illustrates the predictable pattern of monthly dextran levels of sugar delivered to the Durban and Maputo sugar terminals over five seasons. Although all milling areas exhibit similar shaped curves, the absolute levels vary significantly between mills.

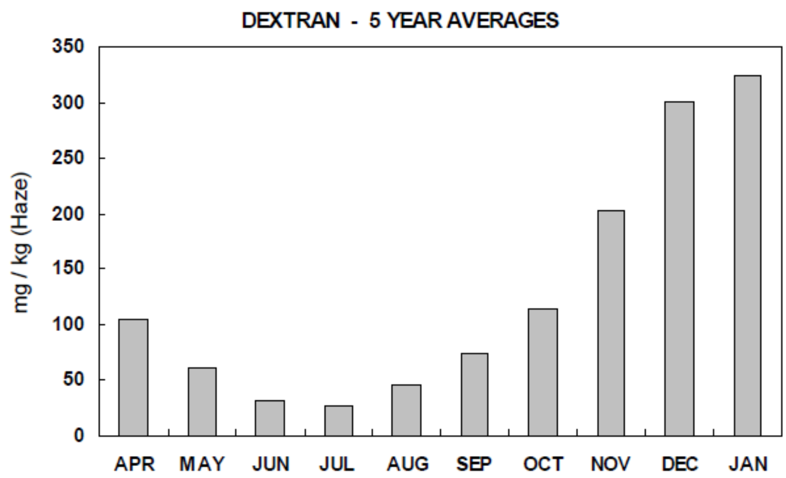


Figure 2.3 Five-year average monthly dextran levels in VHP sugar delivered to the Durban and Maputo sugar terminals (Ravno and Purchase, 2005)

Ravno and Purchase (2005) found that the production of dextran is a function of temperature, moisture and delays between burning/harvesting and crushing. Rainfall leads to increased levels of dextran, most likely due to the result of rain-induced delays between burning and crushing (Grunow *et al.,* 2007). The deterioration rate increases exponentially as temperatures increase (Rangel *et al.*, 2010). Mechanical harvesting that billets cane causes increased rates of deterioration (Ravno and Purchase, 2005). Burnt cane deteriorates faster than unburnt cane (Ravno and Purchase, 2005; Bernhardt and Arnold, 2011). It appears that burnt wet cane also deteriorates faster than burnt dry cane (Ravno and Purchase, 2005). In addition, burnt cane that is left standing deteriorates faster than harvested burnt cane (Wood, 1973). Burning areas for cutting which are too large to be harvested within a day or two must be avoided, because this increases deterioration due to a longer burn to crush delay (Weekes, 2004).

2.4 Transport Capacity and Season Length

Milan *et al.* (2006) suggest that determining the optimal combination of transport means is of great importance when considering sugarcane harvesting. The aim must be to minimise costs, while meeting daily supply obligations with high levels of quality. Transport times should be as short as possible (Stutterheim, 2006).

There are many different transport systems used to move sugarcane from the field to the mill. Transportation accounts for 20-25 per cent of the total cost of producing sugar (Giles *et al.,* 2009). Increasing transport costs is a major factor in the decreasing profitability of sugarcane production (Milan *et al.,* 2006). The daily logistics of mill supply, particularly transport, has been the focus of much research (Lejars *et al.*, 2008).

Transport capacity refers to the total tonnage of cane that can be transported at any point in time. The transport capacity available at a mill area determines the rate of delivery to the mill (Higgins and Muchow, 2003). Greater transport capacity is needed when the length of the milling season is reduced.

2.4.1 Transport utilisation

Better usage of existing transport can allow a shorter milling season (Le Gal *et al.*, 2004). For example, Giles *et al.* (2005) simulated a central fleet control system at the Sezela Mill area, which suggested the potential to reduce the fleet size by at least 60 per cent.

Payload efficiency is a measure of the actual tons of cane delivered, compared to the maximum allowable payload of the vehicle. Increasing payload efficiency can allow a shorter milling season. Factors that affect payload efficiency include the level of trash present in the cane, the physical characteristics of the cane stalks, loading methods used and the skill of the loader operator (de Beer *et al.,* 1989; Wynne and van Antwerpen 2004; Giles *et al.,* 2009; Bernhardt and Arnold, 2011).

2.4.2 Reliable deliveries

An effective transport system is one that provides a constant supply of sugarcane to the mill (Milan *et al*., 2006). Sugarcane deliveries to the mill must be reliable to allow 24-hour operation without excessive stockpiling (Weekes, 2004). Often transport operations will run day and night, while harvesting is only done during the day. Reliable and consistent cane supply to the mill is necessary if the planned LOMS is to be followed.

Kadwa (2012) lists some factors that cause inconsistent deliveries. These include equipment maintenance, unscheduled deliveries, weather conditions, road conditions, accidents and breakdowns. Excess vehicle arrivals and slow turnaround times at the mill can cause disruptions to transport. Driver shift changes can also cause delays and reduce transport capability.

Transport is vulnerable to disruptions caused by wet weather and breakdowns (Higgins and Davies, 2005). Substantial disruptions can lead to costly mill stops. Wet weather is especially disruptive when cane trucks are driven into the field for direct loading, instead of being loaded at a trans-loading zone (Weekes, 2004). When the cane is irrigated, sufficient drying-off periods before harvesting are also important.

2.4.3 Cane yard delays

Long delays in the cane yard increase the burn/harvest to crush delay and can interrupt the whole system. The loading and transport systems found in a mill area influence the offloading system used (Weekes, 2004). There are many different types of offloading systems, but some are far more efficient than others. The quick offloading of trucks at the mill is needed to meet transport requirements (Grunow *et al.*, 2007).

2.4.4 Stockpiling

Stockpiling reduces the risk of no-cane stops and can help ensure constant levels of mill operation, but is constrained by cane deterioration (Barnes *et al.*, 2000; Weekes, 2004; Boote *et al.*, 2011). However, Weekes (2004) states that a level of reserve cane is important to smooth out small disruptions in cane flow to the mill. The reserve cane is used to ensure the continuous and even flow of cane to be crushed. This can prevent a large number of no-cane stops.

Stockpiling is unavoidable when cane is only cut during daylight hours, but the mill operates through the night (Higgins and Davies, 2005). Ideally, a stockpile should be large enough to reduce the chances of the mill stopping due to interruptions in cane supply, but not so big that deterioration impacts mill throughput and extraction efficiency. Cane must be used from a stockpile following a first-in/first-out manner (Weekes, 2004).

Stockpiles can be found at several places in the sugarcane supply chain. The nature of their fluctuations is a good indicator of supply chain efficiency. Bezuidenhout (2010) states that stockpiles can either be deliberately created or occur unexpectedly. Stockpiles are deliberately created to reduce the risk of a disruption in supply, for example, due to approaching bad weather. Unexpected stockpiles can be caused by unwarranted disruptions to cane supply or capacity bottlenecks. Table 2.2 summarises the different stockpiles found in the sugarcane supply chain in South Africa.

Table 2.2 Stockpiles found in a typical South African sugarcane supply chain (Bezuidenhout, 2010)

	Deliberate	**Unexpected**
In-field	Rainfall and night time exposure (average)	Very poor inventory info (bad)
Loading zone	Good but poor inventory info (good)	Poor inventory info (average)
Vehicles (queue)	Expensive and causing bull whipping (bad)	Highly inefficient (bad)
Mill yard	Congested, first-in-first-out (average)	Unnecessary double handling (average)

Bezuidenhout (2010) states that in-field stockpile levels are difficult to monitor and are susceptible to wet weather. In-field stockpiles also inhibit transport at night time. More useful are loading zone stockpiles, but these are still difficult to quantify. Stockpiles at the sugar mill are the most appropriate/useful, but if incorrectly managed, can lead to congestion and the under-utilisation of transport vehicles. Ensuring that a first-in-first-out (FIFO) principle is followed with large mill stockpiles can be difficult. Stockpiling on cane transport vehicles is highly inefficient because it means that expensive capital sits idle for long periods of time.

2.5 Mill Throughput and Production

The throughput of a sugar mill is a key determinant of the length of the harvest season. Season length also has an effect on how much sugar the mill produces and how efficiently it operates. The aim is for the mill to operate at optimum capacity throughout the milling season. Mill throughput can determine season length in three ways (Hildebrand, 1998; Moor and Wynne, 2003):

a) varying mill throughput for a fixed crop of sugarcane,

b) varying the size of the sugarcane crop for a fixed mill throughput, or,

c) varying both mill throughput and crop size.

Throughput is calculated from the hourly crushing capacity, the number of working hours, maintenance time and the frequency of breakdowns (Guilleman *et al.,* 2003; Gaucher *et al.,* 2004). The need for scheduled maintenance, occurrence of public holidays, mill breakdowns and cane supply fluctuations must be taken into account when evaluating the crushing potential (Hildebrand, 1998).

This section will cover (a) milling restrictions, (b) mill stops and Overall Time Efficiency, (c) sugar extraction, and (d) diversions to other mills.

2.5.1 Restrictions to mill throughput

Mill throughput is influenced by cane quality and cane supply (Gaucher *et al.,* 2004; Le Gal *et al.,* 2004; Lejars *et al.,* 2008). The mill is usually designed to process cane of an average quality across the length of the season. This can result in bottlenecks at different processes of the factory, because quality varies during the season (Stutterheim, 2006).

Fibre percent affects crushing and diffuser capacity (Lejars *et al.,* 2008; Bezuidenhout, 2010). According to Graham and Gunn (1971), fibre is a controlling factor in milling throughput and thus high levels of fibre extend the milling season. Lower levels of fibre and a shorter season would reduce the wear and tear on mill equipment and save maintenance costs. However, sufficient fibre is required to run the mill's boilers without needing supplementary fuel. Schorn *et al.* (2005) describe how high fibre levels and the size of the extraction plant can limit throughput at one point of the season. Hildebrand (1998) states that fibre limits throughput towards the end of the season, but Wynne and Groom (2003) state that fibre constraints occur at the start of the season.

Lejars *et al.* (2008) state that brix percent affects the evaporator and crystalliser throughput. In South Africa, restrictive brix loading is often experienced in the middle of the season (Hildebrand, 1998).

Maximum sucrose levels and the size of the high-grade portion of the boiling house restrict throughput (Schorn *et al.,* 2005; Bezuidenhout, 2010). Restrictions due to sucrose occur in the middle of the harvest season (Wynne and Groom, 2003)

Wynne and Groom (2003) state that non-sucrose restrictions occur towards the end of the season. Non-sucrose percent affects the crystalliser capacity (Lejars *et al.,* 2008). Schorn *et al.* (2005) and Bezuidenhout (2010) state that throughput is restricted by non-sucrose levels and the size of the low-grade portion of the boiling house.

If mills are effectively designed, restrictions due to fibre, sucrose and non-sucrose will occur over equal lengths of time during the season (Schorn *et al.,* 2005). Mill components should not be oversized to meet peak requirements that only occur for a short time during the season (Schorn *et al.,* 2005).

2.5.2 Mill stops and Overall Time Efficiency

Mill Overall Time Efficiency (OTE) is a measure used to quantify the amount of time that the mill operates out of the potential time that it can operate (Hildebrand, 1998). OTE changes with cane quality and is also influenced by other factors through the season. Multiplying milling capacity by the OTE gives mill throughput (Hildebrand, 1998; Guilleman *et al.,* 2003).

Mill stops should be minimised because they are costly in terms of idle labour, wasted fuel, and lost juice quality (Weekes, 2004). Wynne and Groom (2003) found that mill stops can be caused by several factors occurring simultaneously. This adds complexity to recording mill stops, which can make the modelling of mill stoppages difficult. Mill stops include stops to allow maintenance, stops caused by a disruption in cane supply, stops caused by the breakdown of milling equipment and stops caused by contaminated cane.

Maintenance stops are scheduled mill stops where the mill is stopped completely (or partly, when there is more than one line) to allow preventative maintenance and cleaning. The stops are important, as maintenance keeps mills running at an acceptable level and reduces the chances of expensive mechanical breakdowns. Fewer unpredictable stops increase mill Overall Time Efficiency. Maintenance stops are normally less than a month apart, but actual timings differ between mills. Milan *et al.* (2006) refer to a certain sugar mill, where technical maintenance is carried out every 10 days, necessitating a complete stop of the mill. Maintenance stops are not always of the same duration.

A no-cane stop occurs when there is a long enough interruption of cane supply to the mill to cause the mill to stop processing. These stops are more common at the beginning and end of the milling season, when rainfall disrupts cane supply (Le Gal *et al.*, 2004; Boote *et al.*, 2011; Kadwa, 2012). Slow crushing refers to when the crush rate is slowed down to prevent a complete stop, but there is a minimum threshold below which cane cannot be crushed (Wynne and Groom, 2003; Kadwa, 2012).

Foreign matter mill stops can be caused by large objects delivered with the sugarcane, such as rocks and pieces of metal (Mann, 1996). Mann (1996) states that although larger objects, such as rocks and pieces of metal, can cause considerable damage to sugar milling equipment, it is sand that is the greatest problem. Graham and Gunn (1971) point out that soil is nearly always present in cane delivered to the mill. Wienese and Reid (1997) estimated that, on average, mill stoppage caused by soil in cane was 50 hours per million tons of cane crushed.

Soil is highly abrasive and damages cane knives, hammers, rollers, pump impellers, pipes and boiler tubes (Graham and Gunn, 1971; Mann, 1996; Wienese and Reid, 1997). Soil also leads to increased sucrose losses, reduces the time efficiency of the mill and requires additional equipment and processes, which are not normally necessary (Wienese and Reid, 1997). More soil is delivered to sugar mills during wet weather (Neethling, 1982; Reid, 1994).

Ash percentage of sugarcane can be used as a measure of contamination by soil, but not all ash is due to soil (Wienese and Reid, 1997). Solid residue from fibre, trash and cane tops makes up a portion of the ash present. For normal quality, soil-free cane, ash was estimated to be in the range of 0.4 to 1.2 percent by Brokensha and Mellet (1977).

Sugarcane with an ash content of greater than 2% causes severe problems at mills that use diffusers. Ash levels of 10% will block a diffuser immediately (Mann, 1996). High ash in the bagasse can extinguish the mill furnaces. An extension of the harvest season increases maintenance stops due to ash, as there are increased mill stoppages towards the end of the season when percentages of ash increase (Kadwa, 2012).

2.5.3 Sugar recovery

Sucrose, non-sucrose and fibre affect milling process efficiency (Gaucher *et al.*, 2004; Le Gal *et al.*, 2004; Le Gal *et al.*, 2008; Lejars *et al.*, 2008). Sugar recovery is partly determined by the decisions growers make when they select their varieties, harvest capacities and management approaches, as these choices affect cane quality (Gaucher *et al.*, 2004). Sucrose extraction becomes more difficult as fibre and non-sucrose contents increase (Guilleman *et al.*, 2003).

Sucrose recovery rate follows a seasonal pattern that peaks towards the middle of the milling season, when quality is highest. Season average sucrose recovery is influenced by the length of milling season (Todd *et al.*, 2004). This effect is illustrated in Figure 2.4. In a shorter season more of the crop is processed when sucrose recovery is near the peak of the curve, which results in a higher season average sucrose recovery rate.

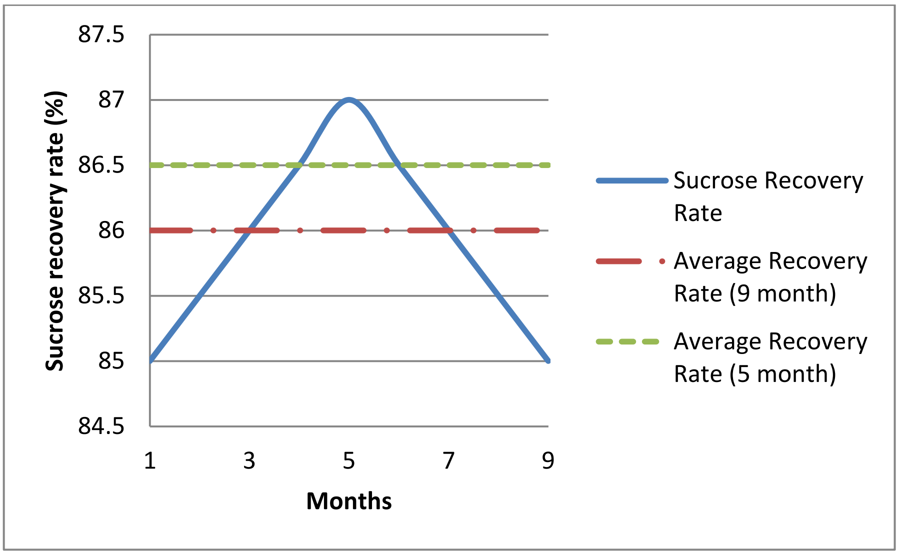


Figure 2.4 Stylised sucrose recovery curve for a typical milling season, showing season average recovery rates for different season lengths (Todd *et al.*, 2004)

As sugarcane deteriorates, sucrose is lost directly when it is converted to glucose by enzymes and micro-organisms (Lionnet, 1996). There is also an indirect loss of sucrose due to the formation of dextrans, which reduce sucrose recovery at the mill. Deterioration also increases the colour of the juices, which leads to higher refining costs. The ratio of dextran level to sucrose loss is not fixed, but at least 0.4 percent of original sucrose has been lost at a dextran level of 1 000 mg/kg brix (Ravno and Purchase, 2005). Figure 2.5 represents an estimated loss curve for overall sucrose recovery at different levels of dextran (Ravno and Purchase, 2005).

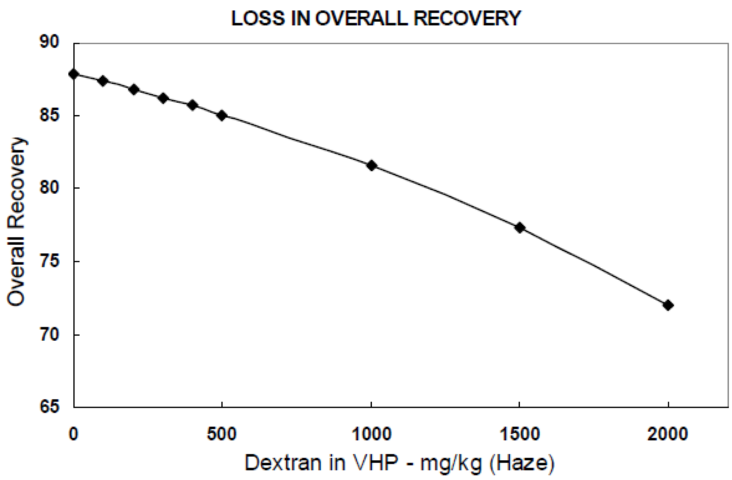


Figure 2.5 Estimated loss in sucrose recovery as a function of dextran content (Ravno and Purchase, 2005)

Normal South African dextran levels are around 200 mg/kg brix, but can be 10 000 mg/kg brix or greater in deteriorated cane (Morel du Boil, 2005; cited by Ravno and Purchase, 2005). Dextran levels above 1000 mg/kg brix are problematic (Ravno and Purchase, 2005). The higher the normal level of dextran, the more vulnerable the mill will be to problems from badly deteriorated sugarcane (Ravno and Purchase, 2005). Morel du Boil and Wienese (2002) state that the dextran level in mixed juice must be below 750 mg/kg brix to achieve a level of 150 mg/kg in raw sugar.

2.5.4 Diversions to other mills

Large sugar companies that operate several mills may divert sugarcane from one mill supply area to another, to reduce under- or over-supply and to maintain the viability of mills and downstream products (Kadwa, 2012). This may extend or shorten the milling season, respectively.

2.6 Literature Review Conclusions

This review has highlighted the factors that determine the acceptability of a particular length of milling season. Many of the identified issues are different for each milling area and change from season to season. The complexity of the milling season decision makes it difficult to define an optimal length.

The operating environment within which a mill is found sets the tone for LOMS discussions and changes. The LOMS decision is complicated further when a variety of different stakeholders' needs and wants must be accounted for. The politics between growers and millers can have an impact on LOMS adjustments. Mill Group Boards, who ultimately determine LOMS, have an important role to play in aiming for increased profitability and competitiveness in the sugarcane supply chain. Cane payment systems could be used by the sugar industry and Mill Group Boards to encourage changes in LOMS, but adjustments to these systems are often difficult to carry out, due to legislation.

The harvesting and transport capacity at a MSA, as well as the efficiency of their use, have an impact on the LOMS. Delays in the supply chain can interrupt milling and hence lengthen the milling season. Harvesting and transport operations are especially vulnerable to delays and disruptions caused by wet weather. Other issues, like heavy frosts and run-away fires, can also affect the supply chain. Factors, such as slow turnaround times at the mill, can influence the efficiency of harvesting and transport systems and have knock-on effects. At certain mills, stockpiles are maintained to reduce the risk of supply chain disruptions, but this has the potential to increase the loss of value from sugarcane, due to deterioration. The majority of sugarcane in South Africa is harvested manually, so the availability and capability of sugarcane cutters could have an influence on the feasibility of shorter season lengths.

The throughput of the mill and the amount of cane to be crushed determine the possible length of the milling season. Mill throughput is also influenced by the quality of sugarcane being crushed and at different times of the season there may be bottlenecks, caused by either the high levels of fibre or sugars. Unplanned mill stops should be avoided as far as possible, but there will always be a need for periodic maintenance stops, and breakdowns are inevitable. The sucrose recovery efficiency of the mill also follows seasonal patterns, which peak when cane quality is highest. Often cane is diverted between mills, to address issues with cane supply or the requirements of downstream processes. These diversions could influence the LOMS.

Of the different factors involved, sugarcane quality stands out as a very important aspect that should be accounted for in any revision of the LOMS. In the past, much work has focussed on modelling sugarcane quality. Quality can be modelled through point based crop growth models or at a wider scale, using regression type methods. Sugarcane quality follows seasonal patterns and is mainly determined by the weather conditions experienced in a mill area. Rainfall and higher temperatures stimulate the growth of sugarcane, which reduces the sugar content of the stalks and increases the fibre percentage.

The fibre content of sugarcane is increased during periods of growth, which, in turn, are caused by rainfall and higher temperatures. Sucrose content is increased as the cane ripens during the winter months when less water and heat are available for growth. As harvested cane deteriorates, the sucrose content is reduced. The rate of deterioration is increased by wet weather and high temperatures, most often experienced during the summer.

The next two chapters focuses on modelling sugarcane quality at a MSA scale to help enable the better modelling of the LOMS when using the LOMZI framework. The improved LOMZI framework is described in Chapter 5.

3. SUGARCANE QUALITY MODEL - METHODOLOGY

The quality of sugarcane crushed at a sugar mill plays an important role in determining the mill supply area's profitability and competitiveness. For this reason, any modelling with the aim of examining the feasibility of different season lengths, must take quality and its seasonal variations into account. It was decided that a model should be developed to predict the quality of sugarcane in any season, which will enhance LOMZI. This chapter describes the methodology of the sugarcane quality model. First, the data used for the quality model is described in detail and then a description of the quality model is provided.

3.1 Sugarcane Quality Data

Sugarcane quality data from two sugar mills, Umfolozi (28° 26' 24" S; 32° 10' 48" E) and Sezela (30° 24' 36" S; 30° 40' 48" E), were accessed from Cane Testing Services (CTS) after permission had been granted by the respective Mill Group Boards. Daily average fibre %, pol % and brix % cane values were obtained for each mill. Data from 2002 to 2012 were accessed for Sezela and data from 2004 to 2012 were accessed for Umfolozi. Only data for cane originating from the Umfolozi or Sezela MSA were used; any data for cane diverted to the mill from other growing regions were ignored.

Cane quality data were gathered in the same manner at both Umfolozi and Sezela. The direct analysis of cane (DAC) methods used by CTS to collect sugarcane quality data, are standardised across the South African sugar industry (Schoonees-Muir *et al.*, 2009). An industry standard set of procedures is followed for the representative sampling of each consignment of cane. This ensures the fair remuneration of each grower delivering cane to the mill. Mill average daily quality values for delivered cane are calculated by weighting the contributions of each consignment by mass (Schoonees-Muir *et al.*, 2009).

For both mill areas, the available seasons were randomly divided for calibration and verification purposes. The model was calibrated using data from the 2003, 2004, 2006, 2008, 2009 and 2010 seasons for the Sezela MSA. The remaining seasons between 2002 and 2012 were set aside for the verification of the model. At Umfolozi, data from the 2004, 2007, 2008, 2010 and 2012 seasons were used to calibrate the model. Data from 2005, 2006, 2009 and 2011 were used to verify the model for the Umfolozi MSA.

3.2 Weather Data

The Umfolozi and Sezela Mills were chosen because they are distinctly different from one another in terms of MSA composure. Although both mills are situated on the east coast of KwaZulu-Natal, Sezela has a more widely distributed cane supply area that stretches further inland. Umfolozi is situated further north than Sezela. Both mill areas can be classified as experiencing sub-tropical agro-climatic conditions.

At Umfolozi, 70% of the cane is supplied from a climatically homogenous area on the Umfolozi Flats (Boote, 2012). Most of the cane is delivered by tramline. In contrast to Umfolozi, Sezela is a more widely distributed mill area, with cane being delivered from three climatically different zones. Le Gal *et al.* (2004) divided the Sezela Mill area into three supply regions, which showed distinctly different seasonal quality curves from one another. These zones were described as coastal, hinterland and inland. Thus, it was expected that the model would produce more coherent results for Umfolozi when rainfall and temperature inputs were at a MSA scale.

Rainfall and temperature data for the Umfolozi and Sezela mill areas were downloaded from the SASRI Weather Web (SASRI, 2013). A MSA spatial scale was selected on the web page for the weather data. At a MSA scale rainfall and temperature values are an average of the readings recorded for the weather stations that fall within the boundaries of the MSA (Sithole, 2013).

3.3 Quality Model Description

The approach in the sugarcane quality model was to use historic quality and weather data for each mill area in order to simulate cane quality at the time of delivery to the sugar mill. This approach is based on an understanding of how rainfall and temperature influence the properties of sugarcane.

The quality of sugarcane depends both on agricultural management and, to a greater degree, on the recent prevailing weather conditions (Malik and Tomar, 2003). The sugarcane quality model is relatively simple and was based on the assumption that strong relationships exist between recent rainfall and temperature averages and the quality of the cane delivered to the sugar mill (Glover, 1971; Inman-Bamber, 1994a; Inman-Bamber *et al.*, 2002; Singels and Bezuidenhout, 2002; Singels *et al.*, 2003).

The preceding 11 weeks' rainfall and temperature averages were used by the model to predict daily average pol %, brix % and fibre % of cane. For the purposes of the model, Week 0 refers to the most recent seven days, Week 1 refers to the seven days before Week 0 and so on, up to Week 10, which was the most distant seven-day period considered. This approach agrees with the drying off recommendations suggested by Donaldson and Bezuidenhout (2000) for average soil depths at various sites in South Africa. Glover (1971) also identified correlations between cane quality and the weather over the preceding three months.

The literature on sugarcane quality differentiates between the short-term and longer-term effects of the weather. The longer term trends of cane quality are driven by rainfall and temperature averages (Glover, 1971). Short term rainfall causes disruptions in the supply chain (Boote, 2012; Kadwa 2012). These disruptions influence cane quality because there is a longer period available for cane to deteriorate between cutting and crushing. Deterioration is also worsened by higher temperatures and wet weather (Ravno and Purchase, 2005).

This led to the idea that sugarcane quality could be predicted by adding the individual effects of recent rainfall, longer term rainfall and temperature experienced over the past few months. The model also took into account that changes to the quality of sugarcane are not instantaneous. There is a delay between the weather experienced and a change in quality, therefore coefficients to weight the importance of certain days or weeks before the date of prediction were included in the model.

The sugarcane quality model assumes that average daily pol %, brix % or fibre % of sugarcane delivered to the sugar mill can be calculated by adding the components presented in Equation 3.1. The remainder of this section covers each component in greater detail.

$$Pol\%, Brix\%, Fibre\% = \begin{pmatrix} Short\ term \\ rainfall\ component \end{pmatrix} + \begin{pmatrix} Longer\ term \\ rainfall\ component \end{pmatrix} + \begin{pmatrix} Temperature \\ component \end{pmatrix} + \begin{pmatrix} Other\ relevant \\ adjustments \end{pmatrix} \quad (3.1)$$

3.3.1 Short-term rainfall component

The short-term rainfall component (in %) was determined by Equation 3.2 and took into account the rainfall over the most recent seven days.

$$\begin{matrix} Short\ term \\ rainfall\ component \end{matrix} = \sum_{d=0}^{6} \alpha_d PF_d \quad (3.2)$$

Where α_d (in $\%.mm^{-1}$) was a calibrated rainfall weighting coefficient for Day *d* in Week 0. On the day of prediction *d* = 0, the previous day d = 1, and so on, up to d = 6.

PF_d (in mm) refers to the effective precipitation for Day *d* in Week 0. The term 'effective precipitation' refers to the fact that when a rainfall event occurs, the sugarcane is unable to make use of all the water available (McGlinchey, 1998). Above a certain depth of rainfall, water is no longer absorbed and stored in the soil. Water is lost to runoff, evaporation and drainage. Some is also lost to interception. To account for these losses, it was assumed that water from a rainfall event was only available up to a certain limit, PF_{max} (in mm). For example, if the effective precipitation limit for a mill area is 10 mm and on a particular day 100 mm falls, the rainfall event will be reflected as only 10 mm of effective rainfall in the model. A lower limit for precipitation was also considered, but gave no statistical significance and resulted in a reduction of model accuracy. This could be an area for more research. PF_d was determined according to Equation 3.3.

$$PF_d = \begin{cases} P_d & |P_d < PF_{max} \\ PF_{max} & |P_d > PF_{max} \end{cases} \quad (3.3)$$

Where: PF_d : the effective precipitation for day *d* (mm)

P_d : rainfall on day *d* of week 0 (mm)

PF_{max} : a daily 'effective' rainfall limit calibrated for each mill area and quality indicator for week 0 (mm)

3.3.2 Longer-term rainfall component

The longer-term rainfall component (in %) was calculated according to Equation 3.4. The 10 weeks before Week 0 were taken into account.

$$\begin{matrix} Long\ term \\ rainfall\ component \end{matrix} = \sum_{i=1}^{10} \gamma_i \bar{P}_i \qquad (3.4)$$

Where γ_i was a calibrated rainfall weighting factor for Week i, in %.d.mm^{-1}. $\bar{P}_i$ was the average daily effective precipitation for Week i (mm.d^{-1}) and was calculated according to Equation 3.5.

$$\bar{P}_i = \frac{1}{7}\sum_{j=0}^{6} \begin{cases} P_j & |P_j < P_{max} \\ P^* & |P_j > P_{max} \end{cases} \qquad (3.5)$$

Where: $\bar{P}_i$: the average daily effective precipitation for week *i* (mm.d^{-1})

P_j : rainfall on day *j* of week *i* (mm)

P_{max} : a daily 'effective' rainfall limit calibrated for each mill area and quality indicator for weeks 1 – 10 (mm)

The daily effective rainfall limit for weeks 1-10, P_{max}, follows the same reasoning described for PF_{max} above. It was expected that $PF_{max} < P_{max}$ because recent rainfall has a direct impact on surface conditions during harvesting, which, in turn, influences cane quality through increased deterioration rates and the inclusion of wet trash. Even a relatively small amount of rainfall can have these effects (Boote, 2012; Kadwa, 2012).

3.3.3 Temperature component

The temperature component (in %) of the quality prediction was calculated by Equation 3.6. The 11 weeks before the date of prediction were taken into account.

$$\begin{matrix} Temperature \\ component \end{matrix} = \sum_{i=0}^{10} \delta_i \overline{HU}_i \qquad (3.6)$$

Where δ_i (in %.d.°C $^{-1}$) was the calibrated heat unit weighting factor for week *i*. The average daily effective heat units for week *i*, $\overline{HU}_i$ (in °C), was calculated according to Equation 3.7.

$$\overline{HU}_i = \frac{1}{7}\sum_{j=0}^{6} \begin{cases} T_j - HU_{base} & |T_j > HU_{base} \\ 0 & |T_j \leq HU_{base} \end{cases} \qquad (3.7)$$

Where: $\overline{HU}_i$: average daily effective heat units for week *i* (°C.d^{-1})

T_j : average temperature for day *j* in week *i* (°C)

$$T_j = \frac{T_{max} + T_{min}}{2}$$

HU_{base} : a calibrated base temperature (°C)

Growth in sugarcane only occurs when temperatures are above a base temperature of 10°C (Inman-Bamber, 1994b). It was hence assumed that the quality parameters of sugarcane will only be influenced by temperature when a certain threshold is exceeded. These observations led to the inclusion of a thermal time approach in the quality model. A base temperature (HU_{base} in °C) was empirically calibrated for individual quality indicators at each MSA.

3.3.4 Other adjustments

A calibration constant $C_{P,B,F}$ (in %) was added to the model. The subscript *P*, *B* or *F* differentiates between the constant for pol %, brix % or fibre %.

The model also incorporates an adjustment to cane quality determined by which day of the week it is, θ_{dow} (in %). These adjustments are based on a study at the Felixton Mill which discovered weekly trends in quality data (Sibomana and Bezuidenhout, 2013). The day-of-the-week adjustments are denoted θ_1 for Monday, θ_2 for Tuesday and so on, up to θ_7 for Sunday. Day-of-the-week adjustments were calibrated for each quality indicator.

In the past, much work has been devoted to investigate post-harvest deterioration (Lionnet, 1996; Loubser, 2002). The processes involved are complex and deterioration is not frequently measured by sugar industries. For these reasons, a reliable and widely applicable model of deterioration has yet to be developed (Bezuidenhout, 2010). Therefore, the sugarcane quality model did not attempt to adjust quality for deterioration and the data that the model uses are collected after post-harvest deterioration has taken place. Deterioration is thus inherently accounted for in the model.

3.3.5 Complete quality equation

The complete model used to predict pol %, brix % and fibre % is presented in Equation 3.8.

$$Pol\%, Brix\%, Fibre\% = C_{P,B,F} + \sum_{d=0}^{6} \alpha_d PF_d + \sum_{i=0}^{10} \gamma_i \bar{P}_i + \sum_{i=0}^{10} \delta_i \overline{HU}_i + \theta_{dow} \qquad (3.8)$$

Where: C : calibration constant (%)

α_d : calibrated rainfall weighting factor for day *d* in week 0 (%.mm^{-1})

γ_i : calibrated rainfall weighting factor for week *i* (%.d.mm^{-1})

δ_i : calibrated heat unit weighting factor for week *i* (%.d. °C^{-1})

PF_d : the effective precipitation for day *d* in week 0 (mm)

$\bar{P}_i$: average daily effective precipitation for week *i* (mm.d^{-1})

$\overline{HU}_i$: average daily effective heat units for week *i* (°C.d^{-1})

θ_{dow} : an adjustment determined by the day of the week (%)

3.4 Model Calibration

The model was developed and calibrated in Microsoft Excel. The same spreadsheet of formulae was used for both model calibration and verification, with only the data being changed for the two processes. The model was calibrated using the Generalised Reduced Gradient (GRG) non-linear function in Solver within Microsoft Excel. The GRG algorithm is used by Solver to optimise non-linear problems (Frontline Systems, 2014). The function uses advanced algorithms to find globally optimum solutions to problems. Each calibration was performed 100 times, using random initial resampling points. The objective function was to maximise R^2 between simulated values and the actual data for brix %, pol % and fibre % cane, by concurrently adjusting constants ($C_{P,B,F}$), rainfall and heat unit limits (PF_{max}, P_{max} and HU_{base}), weekly weighting factors (α_d, γ_i and δ_i) and day-of-the-week factors (θ_{dow}). In total, 98 coefficients were calibrated for each MSA. A set of calibrations would typically take about five hours on a computer with an Intel i5-3470 CPU and four gigabytes of memory.

3.5 Evaluating Individual Component Contributions

The following method was used to evaluate the individual contributions of the components that make up the quality model. After the model had been calibrated for a mill area, the contributions of recent rainfall (Week 0), longer term rainfall (Weeks 1-10), heat units (Weeks 1-11) and day-of-the-week adjustments to simulated values for brix %, pol % and fibre % cane were individually set to 0 and the reduction in the model performance (change in R^2) was recorded. Equation 3.9 was used to measure the reduction in performance. The resulting values are displayed in Table 4.8.

$$\left({R_{with}}^2 - {R_{without}}^2\right) \times 100 \qquad (3.9)$$

Where ${R_{with}}^2$ is the coefficient of determination when all components of the model are included and ${R_{without}}^2$ is the coefficient of determination when a particular component is turned off.

4. SUGARCANE QUALITY MODEL – RESULTS AND DISCUSSION

After a brief introduction and the presentation of some of the results of the quality model, this chapter is divided into three sections. Section 4.1 covers the simulation of both brix % and pol % cane, because these quality parameters are closely linked. Section 4.2 discusses the simulation of fibre % cane and Section 4.3 is a synopsis of the model's performance and its characteristics.

Table 4.1 displays the R^2 between simulated and observed data for brix, pol and fibre % for both mills, achieved during calibration and verification of the sugarcane quality model.

Table 4.1 Coefficients of determination (R^2, Simulated vs. Observed) achieved in the sugarcane quality model during calibration and verification

	Umfolozi			**Sezela**		
	Pol%	**Brix%**	**Fibre%**	**Pol%**	**Brix%**	**Fibre%**
Calibration	0.79	0.81	0.74	0.84	0.85	0.64
Verification	0.73	0.74	0.57	0.63	0.68	0.56

As expected, the values in Table 4.1 show that the model performed better at Umfolozi than Sezela during verification, even though calibration yielded similar R^2 values for both mills. This is due to the more uniform climate at Umfolozi and the use of MSA scale rainfall data. To further quantify model performance, Table 4.2 presents relevant statistical properties of observed and simulated sugarcane quality data for Umfolozi and Sezela.

Table 4.2 Statistical properties of observed and simulated sugarcane quality data for Umfolozi and Sezela

		Umfolozi		Sezela	
		Observed	**Simulated**	**Observed**	**Simulated**
Pol %	**Maximum**	15.46	14.87	15.62	14.75
	Minimum	10.41	10.51	8.68	8.60
	Mean	13.33	13.05	12.99	12.60
	Standard Deviation	0.96	0.92	1.36	1.41
	RMSE	0.58		0.97	
Brix %	**Maximum**	18.04	17.24	17.85	17.24
	Minimum	13.24	13.36	11.04	10.24
	Mean	15.47	15.26	15.16	14.81
	Standard Deviation	0.89	0.89	1.35	1.55
	RMSE	0.52		0.95	
Fibre %	**Maximum**	19.66	17.98	22.20	18.86
	Minimum	11.56	12.97	13.05	14.51
	Mean	14.41	14.65	16.58	16.47
	Standard Deviation	1.10	0.95	1.33	0.95
	RMSE	0.77		0.89	

Table 4.3 presents the constants, effective rainfall limits and base temperatures of the quality model calibrated for Umfolozi and Sezela. Tables 4.4 to 4.6 depict the calibrated daily rainfall, weekly rainfall and heat unit coefficients of the Model. Table 4.7 contains the calibrated day of the week adjustments for the two mills. Refer to Equation 3.8 for a description of the quality model's coefficients, variables and constants.

Table 4.3 Calibrated quality model limits and coefficients for Umfolozi and Sezela

	Umfolozi	**Sezela**	
Pol % Cane:			
C_P	15.95	14.96	(%)
PF_{max}	57.90	5.98	(mm)
P_{max}	12.88	49.38	(mm)
HU_{base}	0	20.85	(°C)
Brix % Cane:			
C_B	16.49	19.24	(%)
PF_{max}	9.64	7.53	(mm)
P_{max}	13.06	62.98	(mm)
HU_{base}	3.45	0.56	(°C)
Fibre % Cane:			
C_F	13.44	15.12	(%)
PF_{max}	4.28	0.26	(mm)
P_{max}	9.80	0.01	(mm)
HU_{base}	21.35	29.74	(°C)

Table 4.4 Calibrated daily rainfall coefficients (α in %.mm^{-1}) for Umfolozi and Sezela

	Umfolozi			**Sezela**		
$\boldsymbol{\alpha_d}$	**Pol%**	**Brix%**	**Fibre%**	**Pol%**	**Brix%**	**Fibre%**
$\boldsymbol{\alpha_0}$	-0.008	-0.019	-0.021	-0.059	-0.060	0.931
$\boldsymbol{\alpha_1}$	-0.022	-0.054	0.023	-0.093	-0.096	0.709
$\boldsymbol{\alpha_2}$	-0.033	-0.053	0.114	-0.066	-0.056	1.305
$\boldsymbol{\alpha_3}$	-0.022	-0.038	0.120	-0.049	-0.044	1.015
$\boldsymbol{\alpha_4}$	-0.017	-0.029	0.138	-0.039	-0.032	0.957
$\boldsymbol{\alpha_5}$	-0.018	-0.032	0.106	-0.039	-0.036	0.953
$\boldsymbol{\alpha_6}$	-0.011	-0.015	0.094	-0.039	-0.033	0.609

Table 4.5 Calibrated weekly rainfall coefficients (γ in %.d.mm^{-1}) for Umfolozi and Sezela

	Umfolozi			Sezela		
γ_i	**Pol%**	**Brix%**	**Fibre%**	**Pol%**	**Brix%**	**Fibre%**
γ_1	-0.086	-0.091	0.232	-0.048	-0.050	144.280
γ_2	-0.059	-0.057	0.144	-0.056	-0.060	144.280
γ_3	-0.069	-0.082	0.065	-0.062	-0.069	73.926
γ_4	-0.109	-0.122	0.085	-0.071	-0.081	67.854
γ_5	-0.119	-0.118	0.050	-0.082	-0.098	61.990
γ_6	-0.116	-0.115	0.054	-0.062	-0.074	32.297
γ_7	-0.112	-0.115	0.079	-0.059	-0.073	-4.888
γ_8	-0.101	-0.120	0.027	-0.072	-0.074	-43.902
γ_9	-0.103	-0.101	0.030	-0.067	-0.067	-84.419
γ_{10}	-0.080	-0.082	0.009	-0.068	-0.066	-112.900

Table 4.6 Calibrated weekly heat unit coefficients (δ in %.d. °C $^{-1}$) for Umfolozi and Sezela

	Umfolozi			Sezela		
δ_i	**Pol%**	**Brix%**	**Fibre%**	**Pol%**	**Brix%**	**Fibre%**
δ_0	0.056	0.084	0.122	-0.111	0.002	144.280
δ_1	-0.005	0.023	0.147	-0.111	-0.025	82.356
δ_2	0.021	0.039	-0.033	-0.018	0.003	121.683
δ_3	0.009	0.023	-0.017	-0.043	-0.009	57.110
δ_4	0.025	0.028	-0.017	-0.046	-0.017	84.675
δ_5	0.028	0.032	-0.055	-0.043	-0.029	60.735
δ_6	0.020	0.012	-0.058	-0.008	-0.026	94.729
δ_7	-0.045	-0.035	-0.084	-0.032	-0.032	144.280
δ_8	-0.056	-0.060	-0.076	-0.034	0.000	144.280
δ_9	-0.071	-0.075	-0.081	-0.009	0.005	23.631
δ_{10}	-0.045	-0.039	-0.066	0.008	0.017	52.092

Table 4.7 Calibrated day-of-the-week adjustments ($\theta\ in$ %) for Umfolozi and Sezela

	Umfolozi			Sezela		
$\boldsymbol{\theta_{dow}}$	**Pol%**	**Brix%**	**Fibre%**	**Pol%**	**Brix%**	**Fibre%**
$\boldsymbol{\theta_1}$	0.0050	0.0195	-0.0823	0.0484	0.0995	0.0049
$\boldsymbol{\theta_2}$	0.0021	0.0097	0.0566	0.0291	0.0562	-0.0173
$\boldsymbol{\theta_3}$	-0.0033	0.0033	0.0091	-0.0197	-0.0239	-0.0142
$\boldsymbol{\theta_4}$	-0.0015	-0.0165	-0.0042	-0.0199	-0.0355	-0.0158
$\boldsymbol{\theta_5}$	-0.0075	-0.0272	0.0052	-0.0098	-0.0201	-0.0110
$\boldsymbol{\theta_6}$	0.0330	0.0283	0.0149	0.0113	-0.0430	-0.0339
$\boldsymbol{\theta_7}$	-0.0278	-0.0171	0.0007	-0.0393	-0.0333	0.0873

Table 4.8 displays the percentage change in R^2, as a measure of the reduction in model accuracy, when different components of the model were switched off. The larger the value in Table 4.8, the greater that component contributes to the quality prediction. A negative value means that model accuracy improved, when a particular component was switched off.

Table 4.8 Reduction in the R^2 (%) when certain components in the quality model were excluded

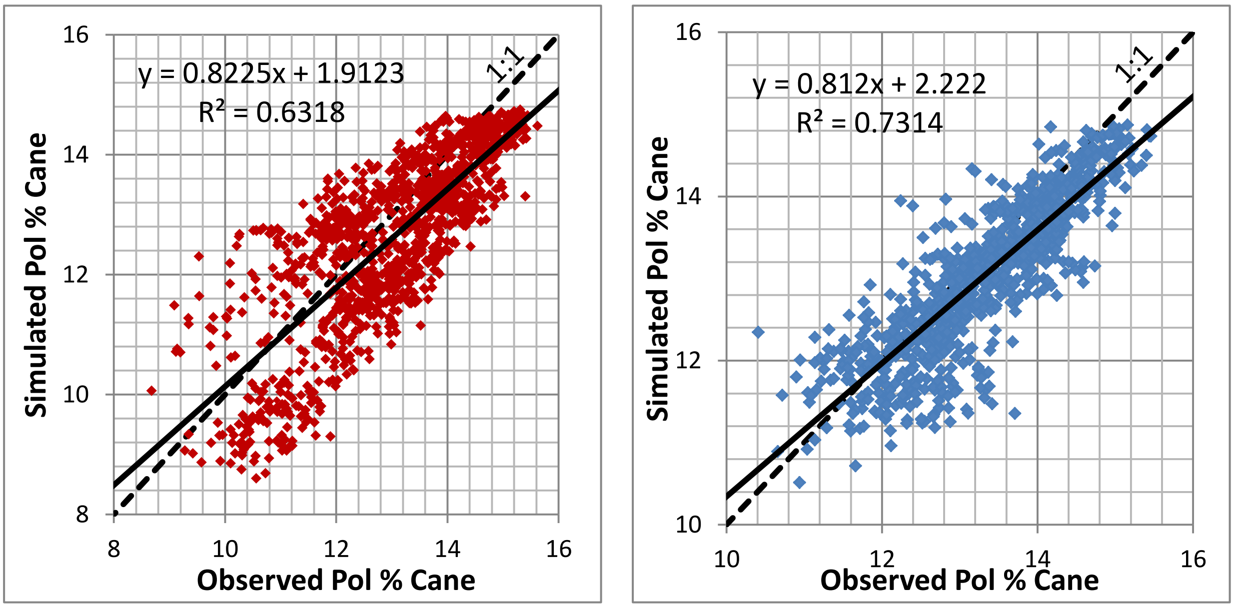
	Umfolozi			Sezela		
Component removed	**Pol%**	**Brix%**	**Fibre%**	**Pol%**	**Brix%**	**Fibre%**
Rainfall Week 0	13.70	18.92	30.36	15.87	17.65	21.43
Rainfall Weeks 1-10	47.95	60.81	17.86	49.21	47.06	25.00
Heat Units	20.55	27.03	46.43	-1.59	1.47	0.00
Day of the Week	0.00	0.00	-1.79	0.00	0.00	0.00

From Table 4.8, it can be seen that longer term rainfall (Weeks 1-10) contributed the most to the predictive capacity of the model for both mills, except for fibre % cane at Umfolozi. At Umfolozi, fibre % cane is more sensitive to heat units. Recent rainfall (Week 0) has a large impact on the predictive capacity of fibre % cane for both mills, but especially at Umfolozi. This is probably because more trash sticks to the cane stalks during wet weather (Booth, 1943; Covas, 1968). For both mills, day-of-the-week adjustments have negligible impacts on model performance and actually reduce model accuracy for fibre % cane at Umfolozi. This indicates that the day-of-the-week factor could be removed from the model without a loss of accuracy for Umfolozi and Sezela. However, day-of-the-week factors did produce interesting weekly trends, which are discussed in the following section. The heat unit segment of the model showed little predictive capacity for quality indicators at Sezela, but had significant impacts at Umfolozi. Again, this is most likely due to the use of MSA scale data at Sezela, where this approach may not be appropriately aggregated.

4.1 Results and Discussion of Modelling Brix % and Pol % Cane

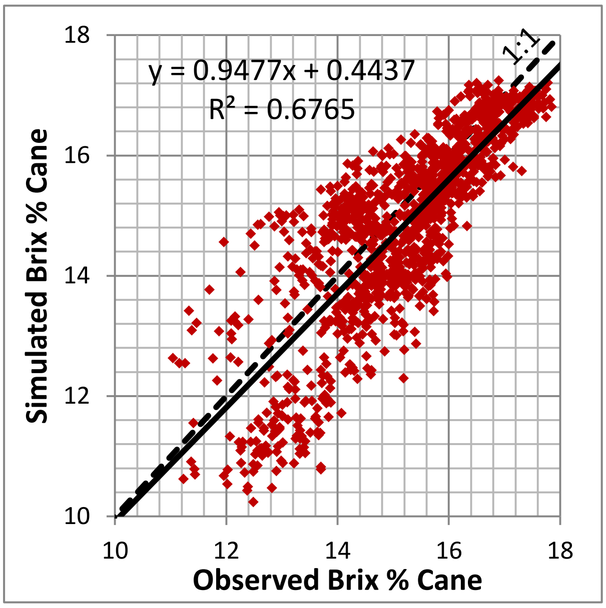
4.1.1 Rainfall responses

Average daily brix and pol % cane were predicted well by the quality model, especially at Umfolozi. Figures 4.1 and 4.2 show that the model marginally under-predicts relatively high pol and brix % cane values, and vice versa. In addition, relatively low values of brix and pol % cane are predicted with lower accuracy, depicted by a wide spread towards the bottom of Figures 4.1 and 4.2. Examining Figure 4.1a, the lower values at Sezela do not seem to be accurately modelled. There seems to be a group of high values and a group of low values, which may indicate that the mill area should be separated into two, for the purpose of predicting quality. Future research could determine how to divide the Sezela MSA and which weather station inputs are most applicable.

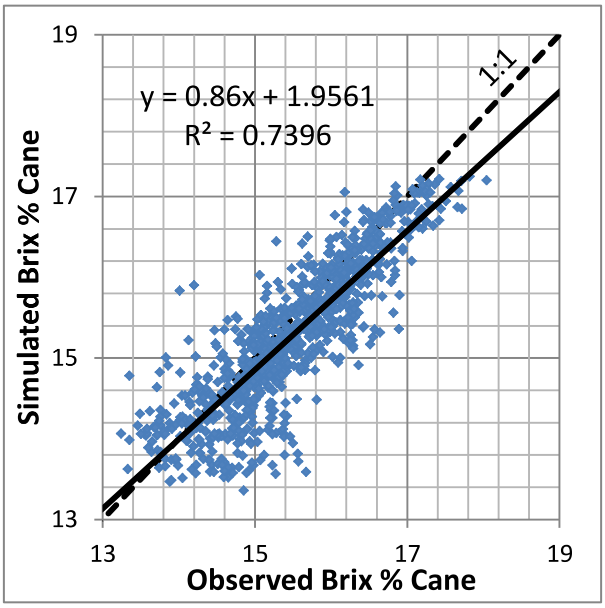


(a) Sezela (b) Umfolozi

Figure 4.1 Simulated vs. observed pol % cane for (a) Sezela and (b) Umfolozi



(a) Sezela



(b) Umfolozi

Figure 4.2 Simulated vs. observed brix % cane for (a) Sezela and (b) Umfolozi

In Figure 4.3, the daily rainfall coefficients (α) for Week 0 show that, at both mills, pol % cane is negatively affected by recent rainfall. This is consistent with Inman-Bamber *et al.* (2002), who report a negative correlation between sucrose content and rainfall occurring up to 14 days before sampling. The reduction in pol % cane, due to recent rainfall, can be ascribed to two causes. Firstly, rainfall prompts growth in sugarcane, which results in a lower pol %, because sugars stored in the stalks are needed to fuel the growth of stalk and leaves (Inman-Bamber *et al.*, 2002). Secondly, rainfall can also cause disruption in the delivery of cane to the mill, which increases the time available for deterioration to occur (Boote, 2012; Kadwa 2012). Deterioration results in the loss and conversion of sugars reflected in lower pol % cane (Ravno and Purchase, 2005).

In Figure 4.3, the coefficients for both mills exhibit a similar pattern, although they differ in magnitude. This difference in magnitude can be partially explained by the different effective rainfall limits (PF_{max}) calibrated for each mill area. Referring to Table 4.3, PF_{max} was 57.90 mm at Umfolozi, while at Sezela it was only 5.98 mm. A small PF_{max} value is likely to result in greater α values due to the multiplicative nature of the quality model. For pol % at Sezela, the maximum response to rainfall is on Day 1, while at Umfolozi it is on Day 2. This could point to a shorter cut to crush delay at Sezela, compared to Umfolozi, but more research is needed to confirm this.

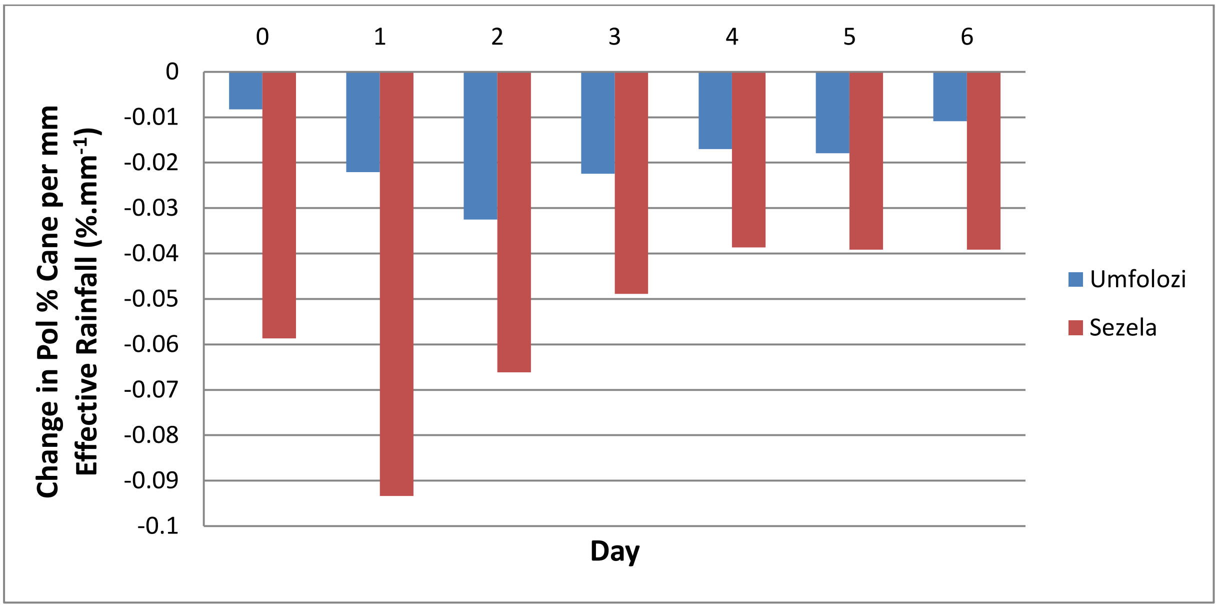


Figure 4.3 Calibrated daily rainfall coefficients (α) for pol % cane at Umfolozi and Sezela

Figure 4.4 shows that brix % cane, like pol %, is reduced by recent rainfall. This is consistent with the findings of Inman-Bamber *et al.* (2002). The daily rainfall coefficients (α) for brix % show less difference between the mill areas than for pol % cane, because the PF_{max} values are similar at 9.64 mm and 7.53 mm for Umfolozi and Sezela, respectively.

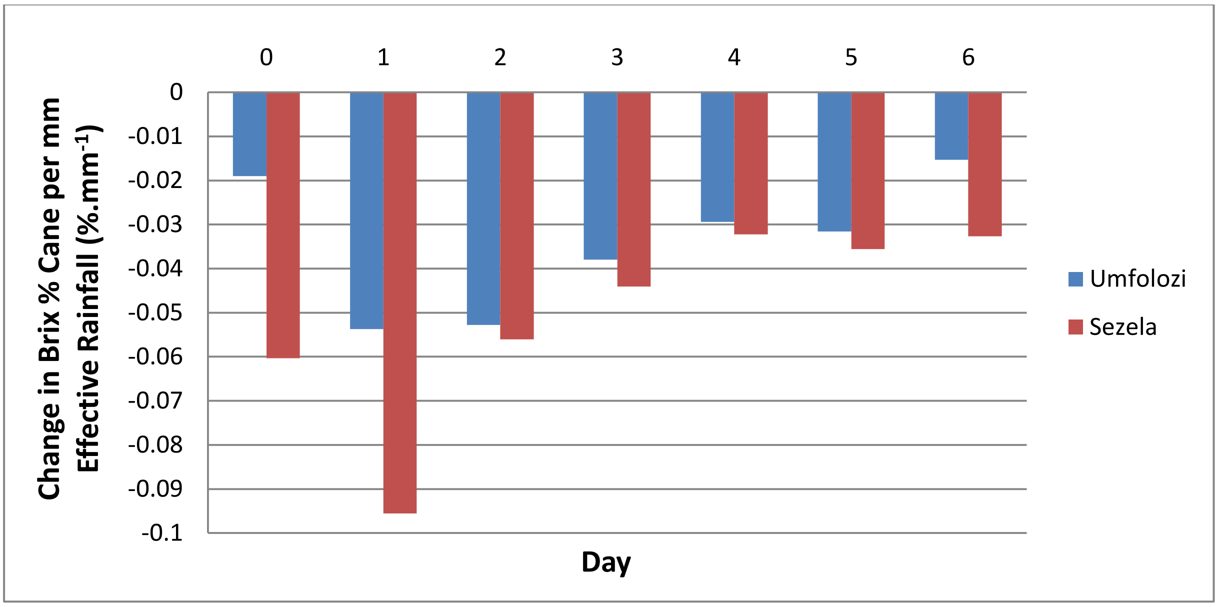


Figure 4.4 Calibrated daily rainfall coefficients (α) for brix % cane at Umfolozi and Sezela

Figures 4.5 and 4.6 compare the weekly rainfall coefficients (γ) for brix and pol % cane calibrated for Umfolozi and Sezela.

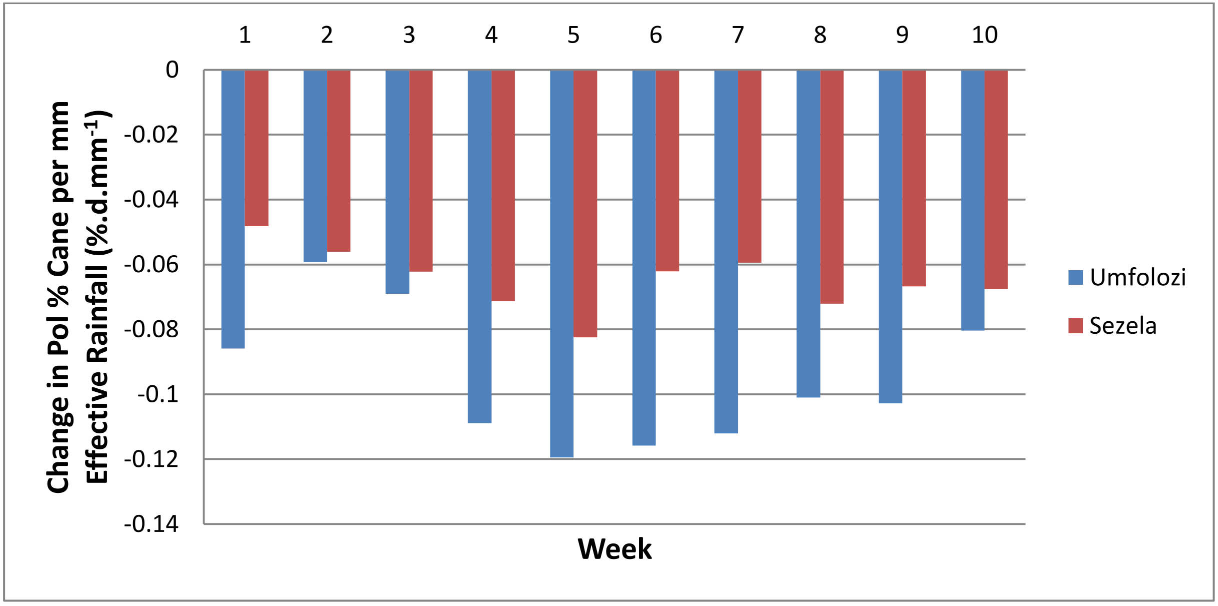


Figure 4.5 Calibrated weekly rainfall coefficients (γ) for pol % cane at Umfolozi and Sezela

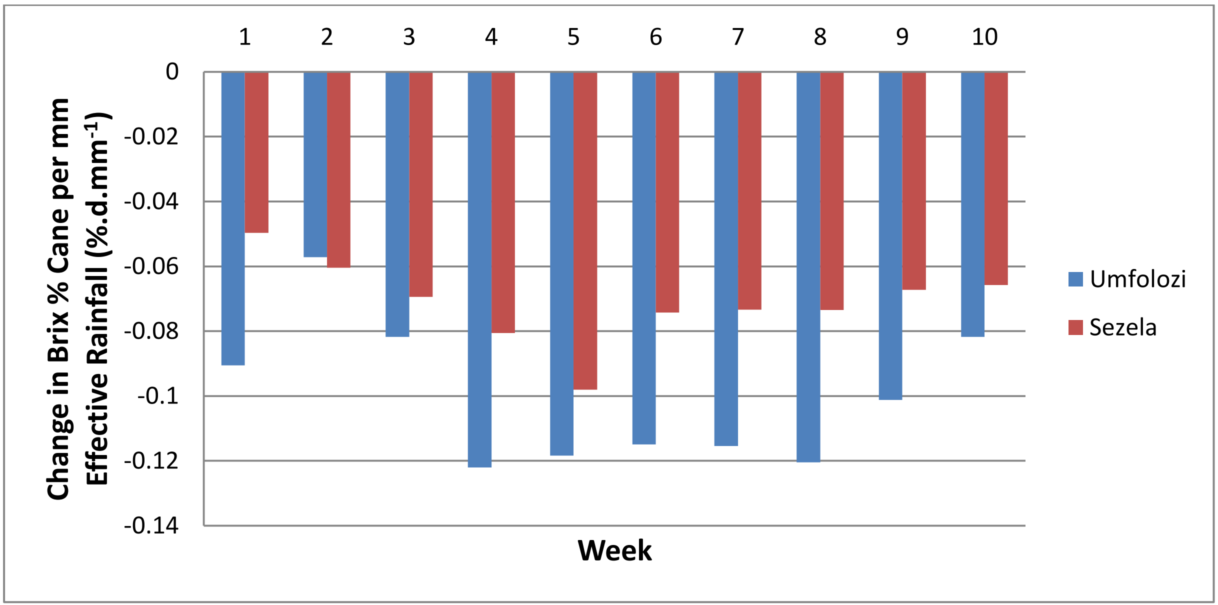


Figure 4.6 Calibrated weekly rainfall coefficients (γ) for brix % cane at Umfolozi and Sezela

For pol % cane, the calibrated effective rainfall limit (P_{max}) was 12.88 mm for Umfolozi and 49.38 mm for Sezela. For brix % cane, P_{max} was calibrated to be 13.06 mm at Umfolozi and 62.98 mm at Sezela. Although the P_{max} values are larger at Sezela, the weekly rainfall coefficients are similar for both mills. This indicates that medium-term rainfall should cause more movement in cane quality at Sezela, compared to Umfolozi. However, the values in Table 4.8 do not agree with this. The variability in model performance, due to rainfall during Weeks 1-10, is similar for Umfolozi and Sezela. For both pol and brix % cane at Umfolozi the γ values for Week 1 are higher than for Weeks 2 and 3, which could indicate that there is a recent rainfall response to precipitation occurring up to 14 days before the date of harvesting, which coincides with the findings of Inman-Bamber *et al.* (2002). The same pattern is not exhibited at Sezela.

The weekly rainfall coefficients in Figures 4.5 and 4.6 show that the longer-term trends of brix % and pol % cane at Umfolozi are driven mostly by rainfall occurring 4 – 8 weeks before the cane is delivered to the mill. The rainfall coefficients for Sezela exhibit a similar, but less pronounced, pattern than the Umfolozi coefficients. At Sezela P_{max} is higher than at Umfolozi, which makes the model more responsive to a range of rainfall events. For both pol and brix % cane at Sezela, the week with the highest calibrated coefficient is Week 5. The calibrated coefficients for both mills agree with Glover (1971), who noted that there was a strong negative correlation between rainfall occurring six weeks before harvesting and the sucrose content of cane for two sites in South Africa. The similar magnitudes and patterns of independently-calibrated rainfall coefficients for two relatively diverse mill areas indicate that the quality model captures some of the physiological responses of sugarcane to rainfall with a fair degree of accuracy.

4.1.2 Temperature responses

Base temperatures at Umfolozi were calibrated at 0°C for pol % cane and 3.45°C for brix % cane. These relatively low base temperatures imply that brix % and pol % cane are adjusted on all days of the year, to account for recent temperatures. Similarly, at Sezela a base temperature of 0.56°C was calibrated for brix % cane. However, a base temperature of 20.85 °C was calibrated for pol % cane. The high base temperature for pol % cane at Sezela generally turns the temperature component off for pol % cane during much of the season. Half the days in the Sezela data (51.5%) did not exceed an average daily temperature of 20.85°C. Table 4.8 shows that heat units have a slight effect on the overall model accuracy at Sezela. For this reason, the respective coefficients, reported in Table 4.6 and Figures 4.7 and

4.8, do not contribute valuably to quality prediction at Sezela. This could explain the large differences between the heat unit coefficients for Sezela and Umfolozi in Figures 4.7 and 4.8. These differences indicate that the daily average temperatures at Sezela at a MSA scale is not necessarily a valuable input for the prediction of pol % cane. A MSA scale for temperature data is not ideal for Sezela, because sugarcane is delivered from coastal and inland growing areas (Le Gal *et al.*, 2004).

The calibrated weekly heat unit coefficients (δ) displayed in Figures 4.7 and 4.8 vary considerably between the two mills, particularly for pol % cane. Inman-Bamber *et al.* (2002) report a negative correlation between recent temperature and sucrose content of sugarcane. The Sezela coefficients match this observation, but have little effect on the model accuracy. At Umfolozi, recent temperatures have a positive correlation with pol % and brix % cane. The heat units in Week 0 contribute positively to pol and brix % cane, although higher temperatures would be expected to increase the rate of deterioration (Ravno and Purchase, 2005). This may be attributed to the benefit of drier fields in Week 0, reducing the delay between cutting and crushing, and perhaps also a loss of moisture from cane during hot weather, promoting higher brix % and pol % cane concentrations at the time of milling. Lyne and Meyer (2005) reported growers who deliberately delay cane deliveries after cutting because of a positive response in recoverable value. The negative correlation for Weeks 7-10 agrees with that of Glover (1971), who found a similar relationship between sucrose % cane and minimum temperatures experienced three months before the date of sampling. Higher temperatures can sometimes promote a drying-off effect (Glover, 1971). It should be noted that the heat unit component of the model captured in excess of 20% of the variability at Umfolozi (see Table 4.8) and is probably worth investigating further.

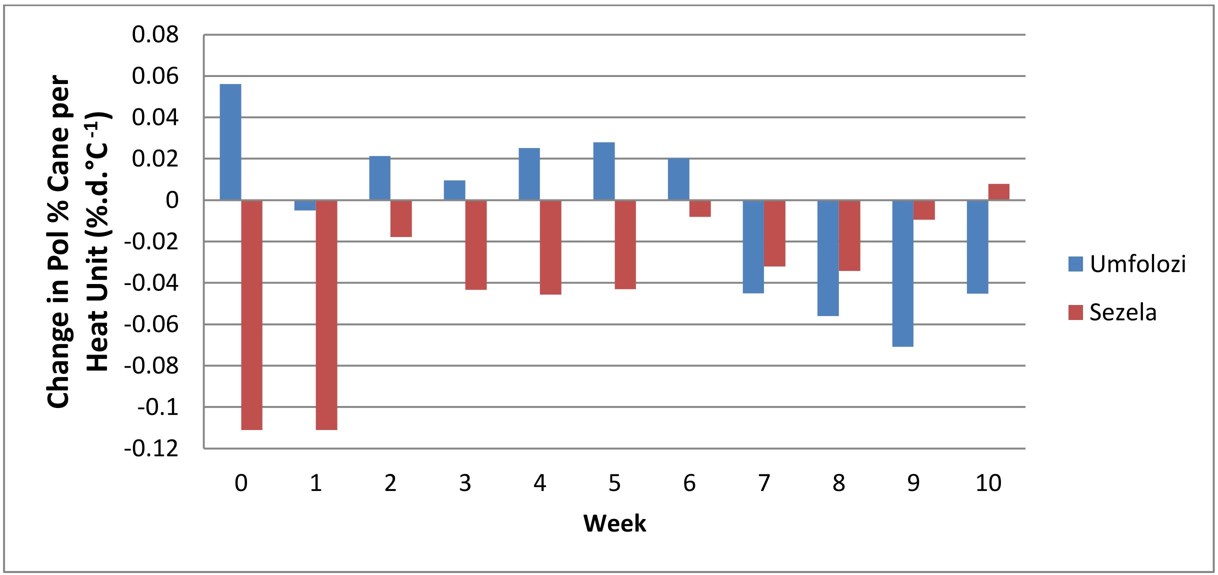


Figure 4.7 Weekly heat unit coefficients (δ) for pol % cane at Umfolozi and Sezela

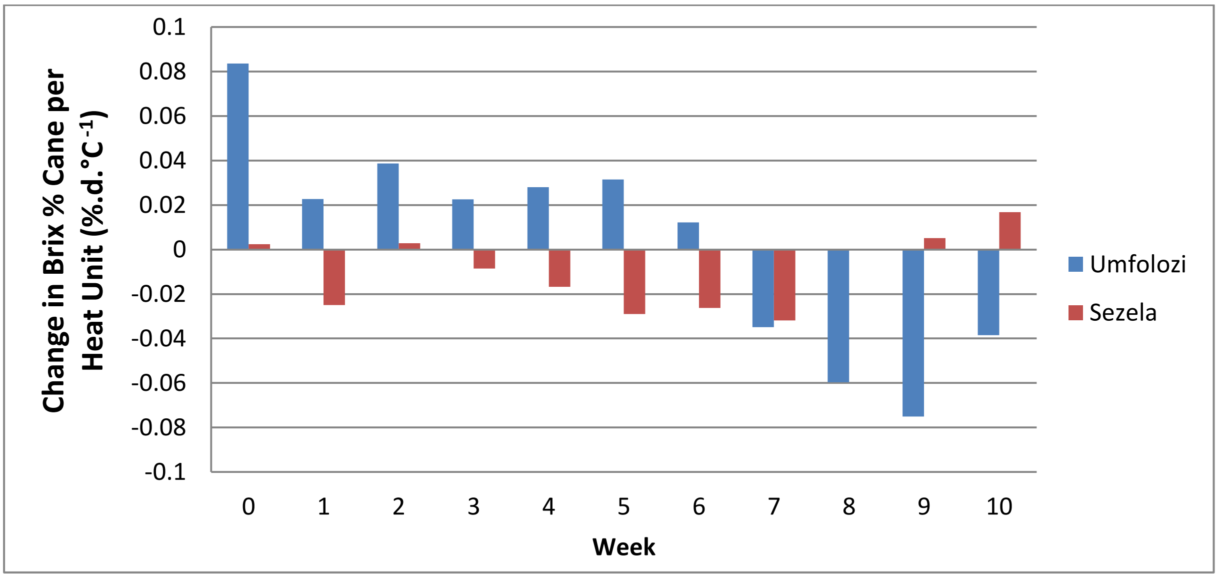


Figure 4.8 Weekly heat unit coefficients (δ) for brix % cane at Umfolozi and Sezela

4.1.3 Day-of-the-week responses

The day-of-the-week adjustments did not substantially contribute to model accuracy and the coefficients are probably not of any importance. However, some of the patterns that emerged could be explained. The day-of-the-week adjustments for brix and pol % cane, in Figures 4.9 and 4.10, show similar patterns at both mills. Apart from different magnitudes, both MSAs have a small positive quality adjustment at the start of the week, while quality is slightly reduced towards the end of the week. Quality adjustments are positive on Saturday, but negative on Sunday. This cycle can partly be explained by the weekly operations on many farms, where cutting is often suspended over weekends. Fields are burnt on a Monday morning, usually a sufficient area for a few days' cutting. This means that cane delivered on a Monday is usually fresh and can explain the high quality recorded at the mill. As the week progresses and burnt cane has more time to deteriorate, the quality drops. The reason for the Saturday increase in quality is not clear. It could be that certain growers (e.g. small-scale growers) do not deliver over weekends. Further research could improve the understanding of these weekly cycles.

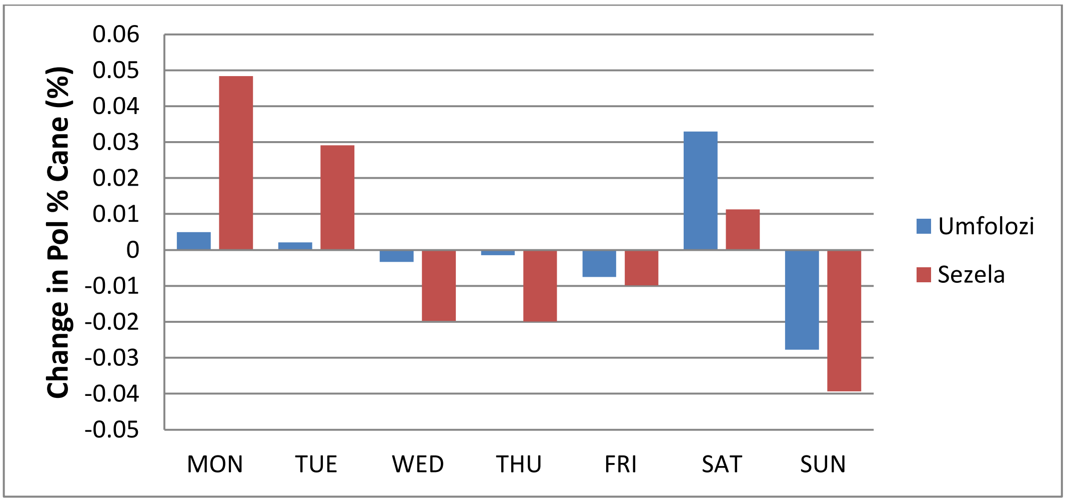


Figure 4.9 Day-of-the-week adjustments (θ) for pol % cane at Umfolozi and Sezela

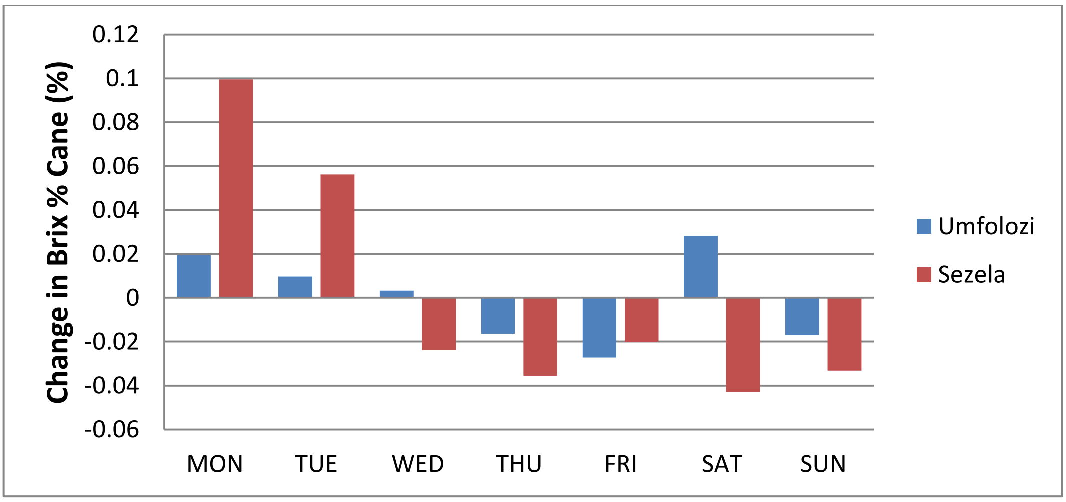
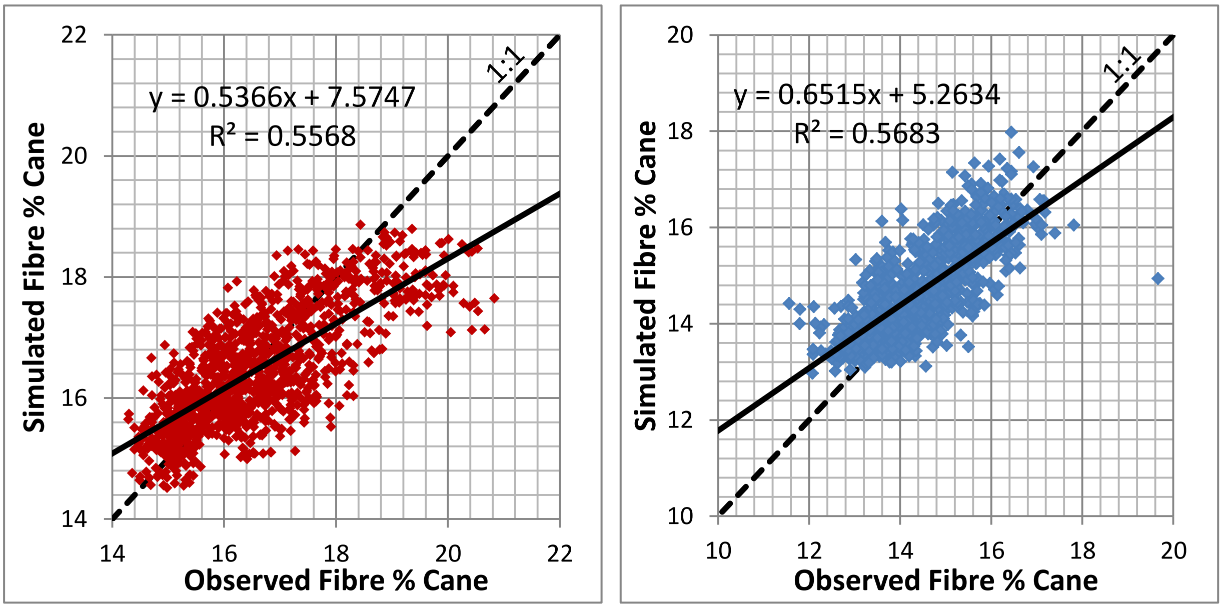


Figure 4.10 Day-of-the-week adjustments (θ) for brix % cane at Umfolozi and Sezela

4.2 Results and Discussion of Modelling Fibre % Cane

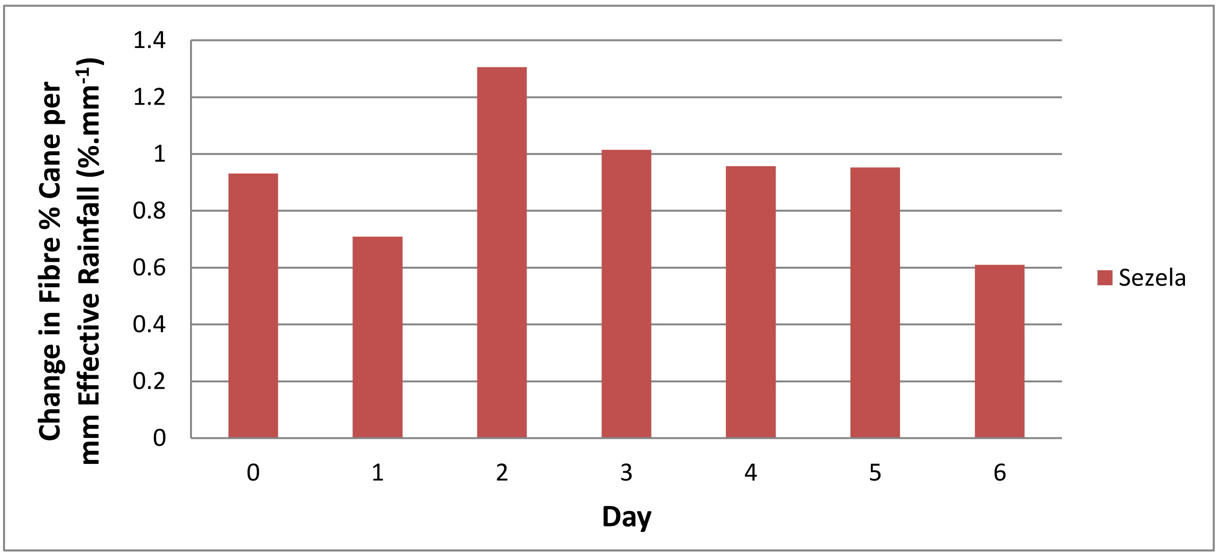
Compared to brix % and pol %, fibre % cane was relatively poorly simulated by the quality model, as depicted in Figure 4.11 and evident in Table 4.1. This is likely because fibre % in sugarcane does not fluctuate as much as pol % or brix % over the season. An R^2 of 0.56 for Sezela and 0.57 for Umfolozi was achieved. Higher values of fibre % cane tend to be under-predicted and lower values are slightly over-predicted for both mills.



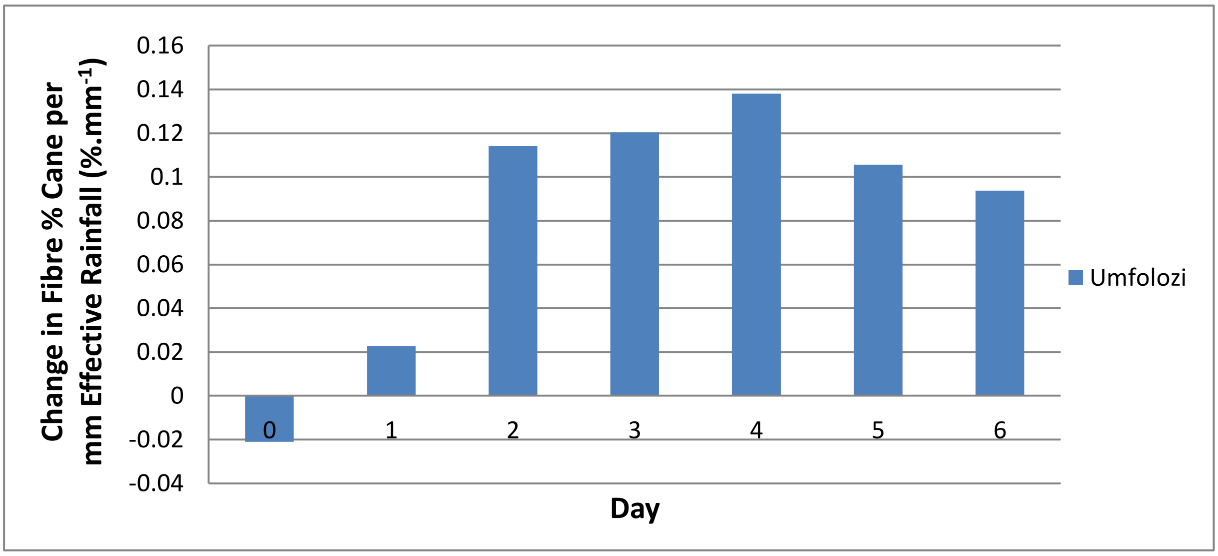
(a) Sezela (b) Umfolozi

Figure 4.11 Simulated vs. observed fibre % cane at (a) Sezela and (b) Umfolozi

Figure 4.12 compares the daily rainfall coefficients (α) at Umfolozi and Sezela. The coefficient magnitudes are greater at Sezela than at Umfolozi. However, the daily effective rainfall limit (PF_{max}) for Sezela was 0.26 mm, while at Umfolozi it was 4.28 mm. This can explain the differences in rainfall coefficient magnitudes between the two mills. Fibre % cane at Umfolozi was better predicted by the preceding seven days (Figure 4.12b), while at Sezela it was better predicted by the previous ten weeks (Figure 4.13a).



(a) Sezela



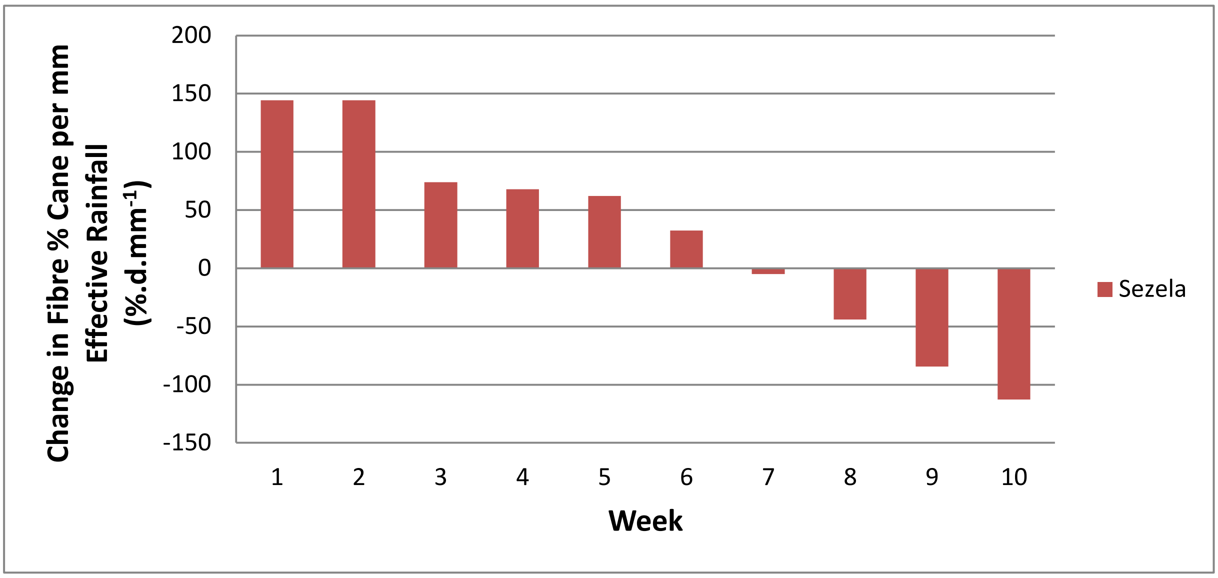
(b) Umfolozi

Figure 4.12 Calibrated daily rainfall coefficients (α) for fibre % cane at (a) Sezela and (b) Umfolozi

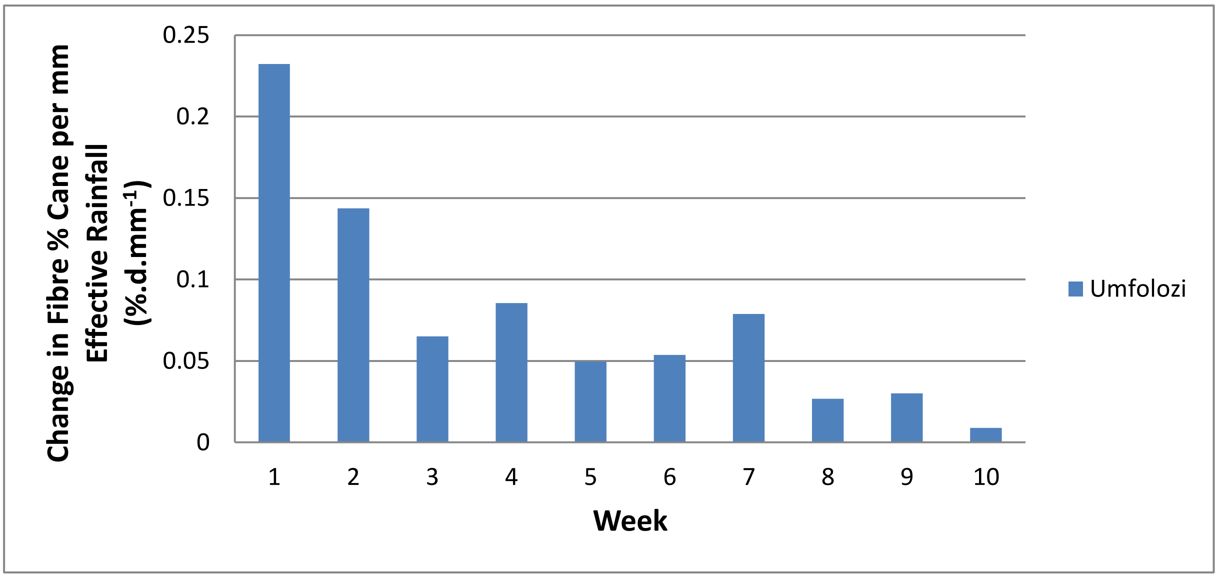
Recent rainfall increases the fibre % cane, which is probably due to more leaves and trash adhering to the cane stalks during wet weather (Booth, 1943; Covas, 1968). This relationship is reflected in the calibrated daily rainfall coefficients. Overall, a positive correlation between any recent rainfall and fibre % cane is displayed in Figure 4.12 at both mills.

The delay between burning/cutting sugarcane and crushing at the sugar mill (BHTCD) has a significant effect on cane quality. A useful estimation of the burn/cut to crush delay may be made from the calibrated daily fibre % rainfall coefficients for a MSA. The coefficients calibrated for Umfolozi (Figure 4.12b) show a rapid increase in fibre % cane two days after a rainfall event. This suggests that, on average, cane may have taken at least two days to arrive at the mill after being cut. Different mills may have different profiles, depending on the average number of days that the cane takes to arrive at the mill. At Sezela the rainfall coefficient for Day 2 also shows a rise in magnitude, although the coefficients of the first two days are also not low.

The weekly rainfall coefficients (γ), shown in Figure 4.13, are much greater for Sezela than for Umfolozi. The effective daily rainfall limits for Weeks 1-10 (P_{max}) are 0.005 mm and 9.80 mm for Sezela and Umfolozi, respectively. This implies that rainfall is a binary variable with respect to fibre % cane at Sezela. Fibre % cane is therefore regulated by the number of rainy days, as opposed to the amount of rain that fell. The extremely low rainfall limit for Sezela explains the relatively high weekly rainfall coefficients calibrated for the MSA. Ignoring the differences in magnitude, both mills show similar patterns in their rainfall coefficients. Recent rainfall has a positive correlation on fibre % cane, while rainfall during weeks further in the past have a diminishing influence. The decrease in magnitude is more pronounced at Sezela. By Week 7, rainfall displays a negative correlation with fibre % cane. All the weekly coefficients for Umfolozi are positive, but become close to zero by Week 10. The importance of recent rainfall on fibre % cane is evident by the relatively large size of the calibrated coefficients for Weeks 1 and 2 and by the fact that between 17 and 25% of the variability was captured by this component of the model (see Table 4.8).



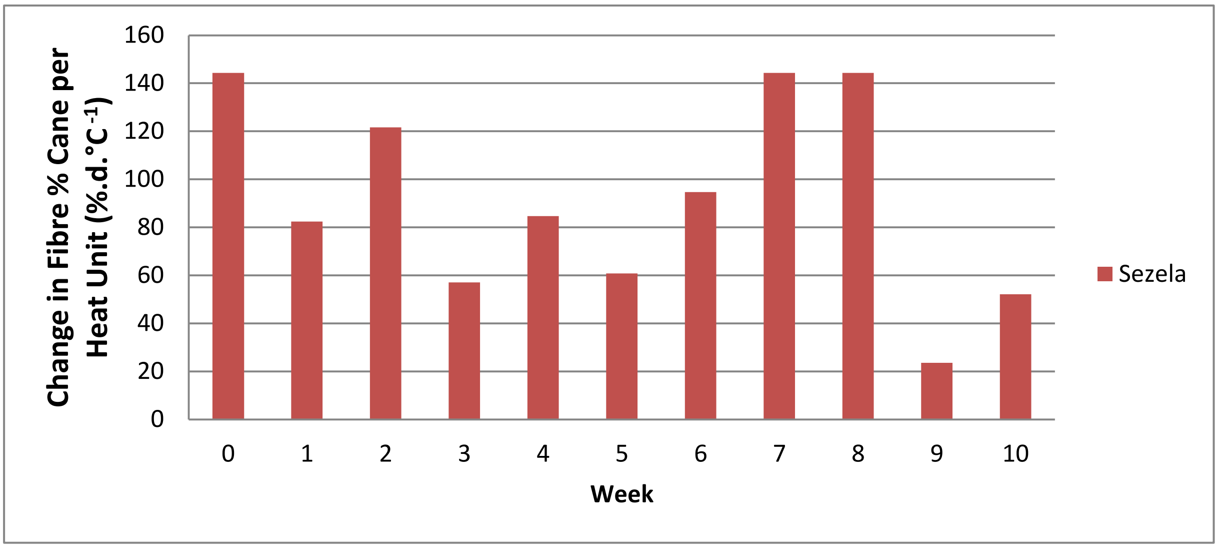
(a) Sezela



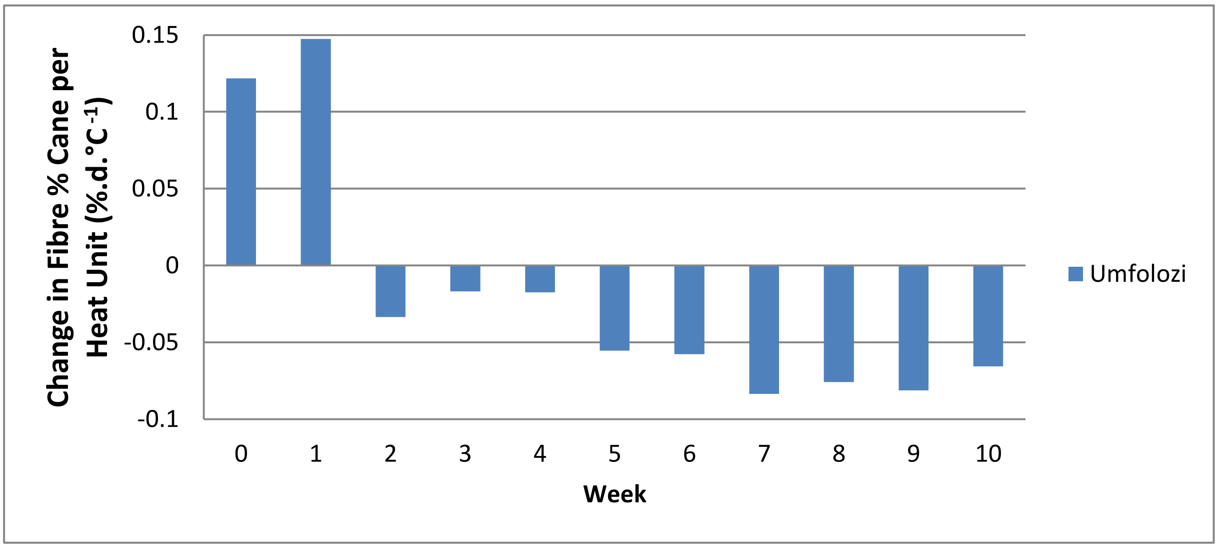
(b) Umfolozi

Figure 4.13 Calibrated weekly rainfall coefficients (γ) for fibre % cane at (a) Sezela and (b) Umfolozi

The weekly heat unit coefficients (δ) for fibre % cane are displayed in Figure 4.14. At Umfolozi, the calibrated base temperature was 21.35°C. At Sezela, the base temperature was 29.74°C and, when referring to Table 4.8, it is evident that heat units have minimal impact on fibre % cane. It should be noted that none of the base temperatures calibrated for pol %, brix % or fibre % cane are similar to the base temperature for the growth of sugarcane reported by Inman-Bamber (1994b). This justifies further research, although it can be anticipated that several other processes, not linked to cane growth, can influence cane quality, such as deterioration, labour productivity and thermal dynamics in stockpiles.



(a) Sezela



(b) Umfolozi

Figure 4.14 Weekly heat unit coefficients (δ) for fibre% cane at (a) Sezela and (b) Umfolozi

Because of the high base temperature and small influence on model accuracy (see Table 4.8), no discernable pattern exists for the Sezela heat unit coefficients in Figure 4.14a. This is probably because only one weather record was used to represent a wide range of cane from different climatic areas. More research to link temperature observations to quality at the correct scale is warranted. The Umfolozi coefficients (Figure 4.14b) show a positive correlation between heat units and fibre % cane for Weeks 0-1 and a small, but negative, correlation for the remaining weeks. The Umfolozi coefficients illustrate the importance of short-term temperature on fibre % cane and captured 46% of the variability, as shown in Table 4.8.

Figure 4.15 displays day-of-the-week adjustments for fibre % cane at Umfolozi and Sezela. Unlike for brix and pol % cane, the fibre % coefficients are distinctly different for each mill. The Umfolozi fibre % adjustment is negative on Monday, positive on Tuesday and very small on the remaining days of the week. At Sezela, the fibre % adjustments are marginally negative, except on Sundays. These adjustments made no significant improvement in model accuracy (see Table 4.8).

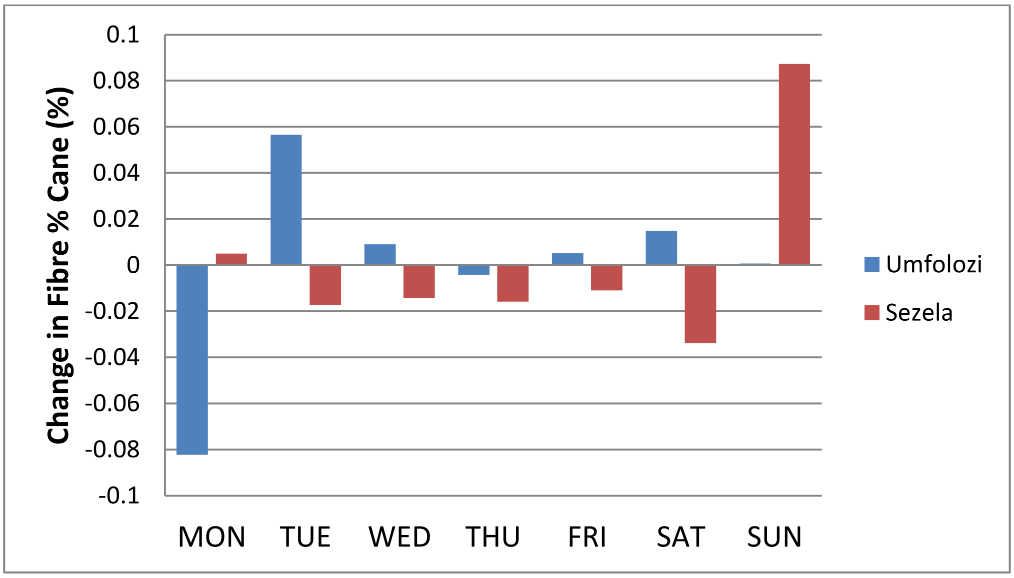


Figure 4.15 Day of the week adjustments (θ) for fibre % cane at Umfolozi and Sezela

Unlike sugars, the fibre in sugarcane does not undergo any chemical or physical changes between cutting and arriving at the sugar mill and thus the mass of fibre remains constant, although its percentage, as part of total sugarcane mass, will change (Loubser, 2002). Thus, it is to be expected that day-of-the-week adjustments to fibre % cane will be minimal.

4.3 Synopsis

Figure 4.16 displays a typical example of simulated and observed quality values, in this case for the 2005 season at Umfolozi. The model (in blue) is good at predicting the general trend of quality over the season, but does not always display the short-term variations and oscillations present in the observed data (in green). At times, an offset between the simulated and observed data exists. The model was unable to predict certain sharp changes in quality, such as at the beginnings of August and October 2005. This indicates that these drops in quality may not be related to rainfall or temperature.

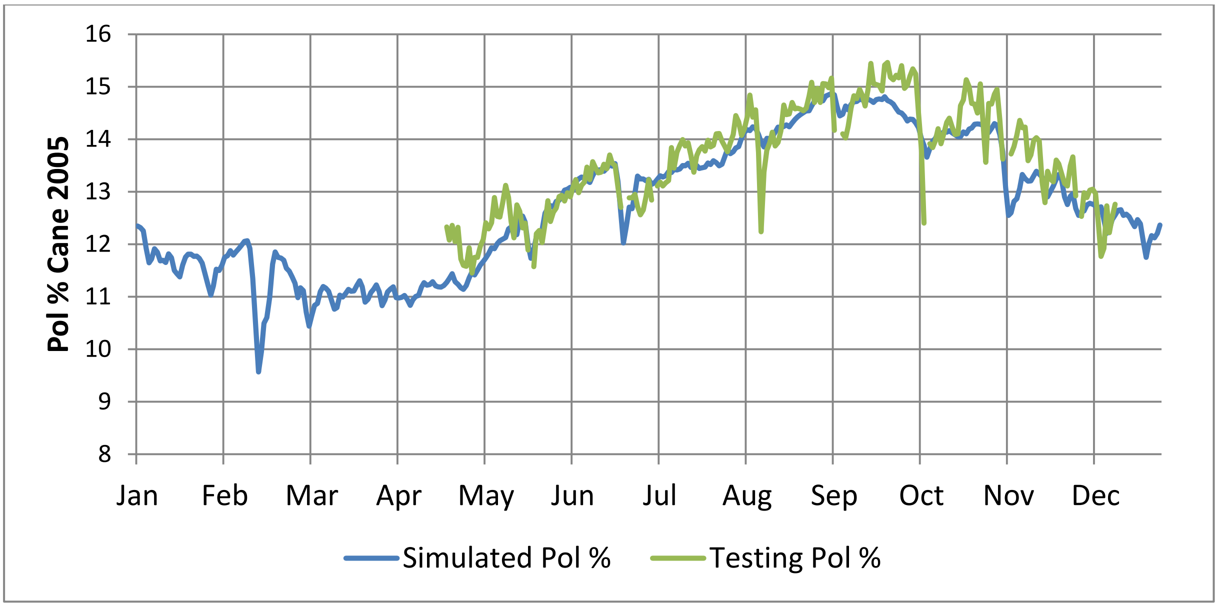


Figure 4.16 Simulated and observed pol % cane for the 2005 season at Umfolozi

The South African milling season usually runs from April to December, which means that the quality model has been calibrated without quality data between January and March for most years. Any quality predictions from the model for the off-season months should be treated with caution. It is difficult to assess the ability of the model to predict quality for these periods because insufficient data exist. Future research could focus on this topic.

Cane purity is determined by dividing pol % cane by brix % cane and is expressed as a percentage. A purity value of 100%, or above, should not occur. In the quality model, brix % and pol % cane were independently calibrated, which could have led to unrealistic purity values. Purity was calculated, using simulated pol and brix % cane, and compared to observed purity values for Umfolozi and Sezela. The model tends to slightly under-predict purity, but did not generate unrealistic values.

Neither cane quality nor weather variables are independent of each other. For example, when it rains it is likely to be cooler and when fibre % cane is higher, brix % cane tends to be lower. The quality model calibration process chooses the best coefficients to fit the data and some of the patterns that emerge may have been due to secondary, but significant, relationships between variables. As an example, some of the temperature responses could be captured in rainfall, because it often rains in the warmer months. This could possibly reduce the ease of discerning patterns by examining coefficient values. The calibration of the model could also be affected by other issues, besides rainfall and temperature, which influence sugarcane quality, for example, frequent mill breakdowns, poor farm management and varieties of cane that mature at different times of the season.

There is a degree of redundancy in the quality model which allows for a wide range of calibration outcomes. There is the possibility of some segments of the model being "turned off" from the calibration process, but this is not a concern. Rather, it makes the model more resilient and probably applicable at a wider range of mills. Although there is a wide range of possible calibration outcomes, the model remains a relatively mechanistic approach to predicting sugarcane quality variables and the researcher is able to make sense of the patterns observed in coefficient values. However, a caveat is that in cases where insufficient data exist, and an independent verification is not possible, this technique may have too many degrees of freedom and allow the model to be calibrated too specifically against the data.

Overall, the model simulates quality at an appropriate and valuable scale. MSA scale quality predictions can be used to aid planning and are of interest to both growers and millers. The impact of every wet spell or heat wave on cane quality can be estimated with relative ease. An important area for potential future research is to find the most appropriate combination of weather statistics to maximise model accuracy for a particular MSA.

5. SUGARCANE SUPPLY CHAIN MODEL DESCRIPTION

LOMZI is a mill area scale, stochastic mechanistic model that runs on a daily time step. The model has evolved from the original version of LOMZI, developed by Boote (2012). The model simulates the sugarcane supply chain from the point of cutting in the field to the delivery of cane at the mill yard. Future work plans to include the milling processes as well. The central idea of the model is that, for each harvesting season, there is a certain amount of sugarcane that must be processed by the mill. Given the daily harvesting capability of the supply chain and the various factors, such as rainfall, temperature, weekends and cane quality that limit this capability, the harvesting season continues until all the available sugarcane is processed.

This chapter provides an in-depth description of LOMZI. First, an overview of the model structure is provided and then each segment of the model is described in more detail. The final part of this chapter explains how the quality model, described in Chapters 3 and 4, has been incorporated into LOMZI. A key objective of the chapter is to illustrate the relationships and assumptions, which were largely based on the literature.

5.1 Model Structure

In LOMZI, it is assumed that, for a particular season, there is a total amount of sugarcane that must be harvested and this total remains constant throughout the season. This is a simplification of the real world. The total amount of sugarcane, in tons, divided by a planned LOMS provides a daily target of cane to be processed in the mill supply area (MSA). The ability of the sugarcane supply chain to meet each day’s cutting target depends on the simulated cutting capability available on that day. Once cane has been cut, it becomes part of an in-field stockpile, from where it can either be extracted to a trans-loading zone or transported directly to the sugar mill. This option depends on the operations favoured in the particular MSA. The daily amount of cane extracted from the in-field stockpile is controlled by the simulated extraction capability available on that particular day. Finally, the amount of sugarcane reaching the sugar mill is controlled by the simulated transport capability available each day. Cane delivered to the sugar mill becomes part of the mill yard stockpile. Figure 5.1 diagrammatically represents one sugarcane supply line, as represented in LOMZI.

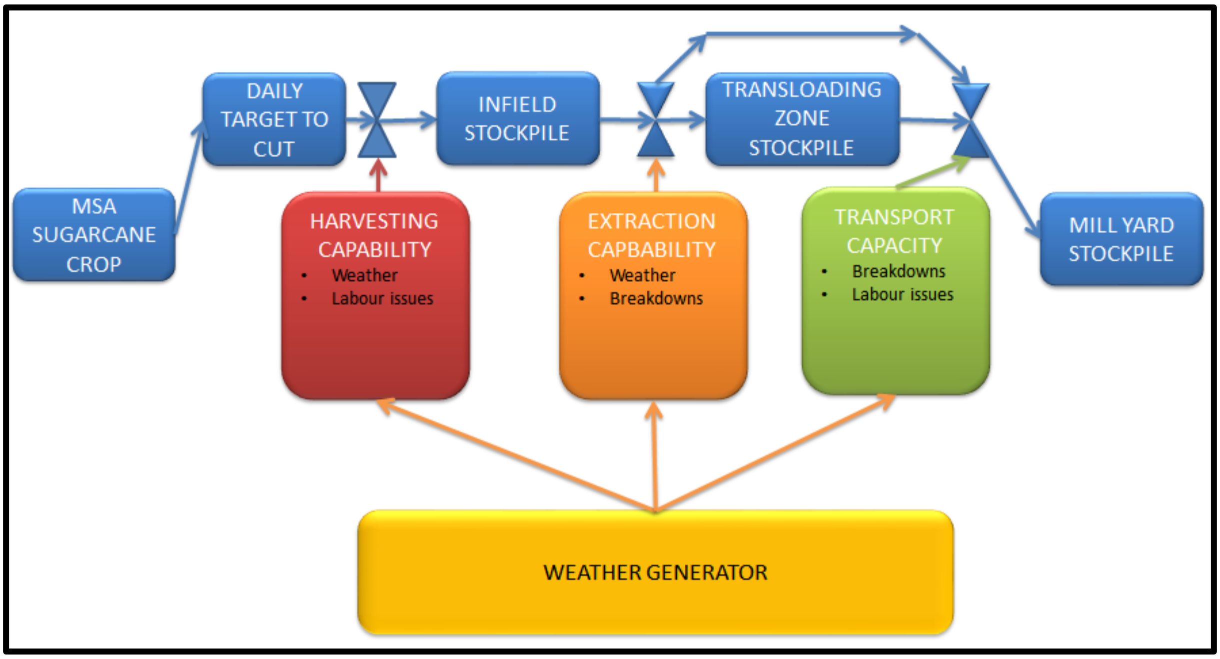


Figure 5.1 LOMZI sugarcane supply line structure

In Figure 5.1, it can be seen that a weather generator is linked to the harvesting, extraction and transport capability blocks. This is because these capabilities are, to a great extent, controlled by the weather conditions experienced in the mill area (Hildebrand, 1998; Weekes, 2004; Higgins and Davies, 2005; Rangel *et al.*, 2010; Boote *et al.*, 2011; Kadwa, 2012). The embedded weather generator serves the purpose of ensuring consistency in the model. For example, rainfall in the model should reduce harvesting capability and extraction capability on the same days. Section 5.2 describes the weather generator in more detail.

Figure 5.2 provides an overview of the LOMZI structure when it is applied to a MSA. The total sugarcane crop for a mill supply area is divided amongst several supply lines. Each supply line represents a uniform zone in the mill area. Different zones could be based on different rainfall and temperatures regimes, and/or different ownership and management structures. Many possibilities exist for dividing a mill supply area into different zones and are likely to be different for each MSA. Mill specific modelling would require the delineation of the appropriate zones based on the local knowledge of millers and growers, as well as observations from industry data. As LOMZI currently stands, up to 10 harvest zones can be defined for a mill area.

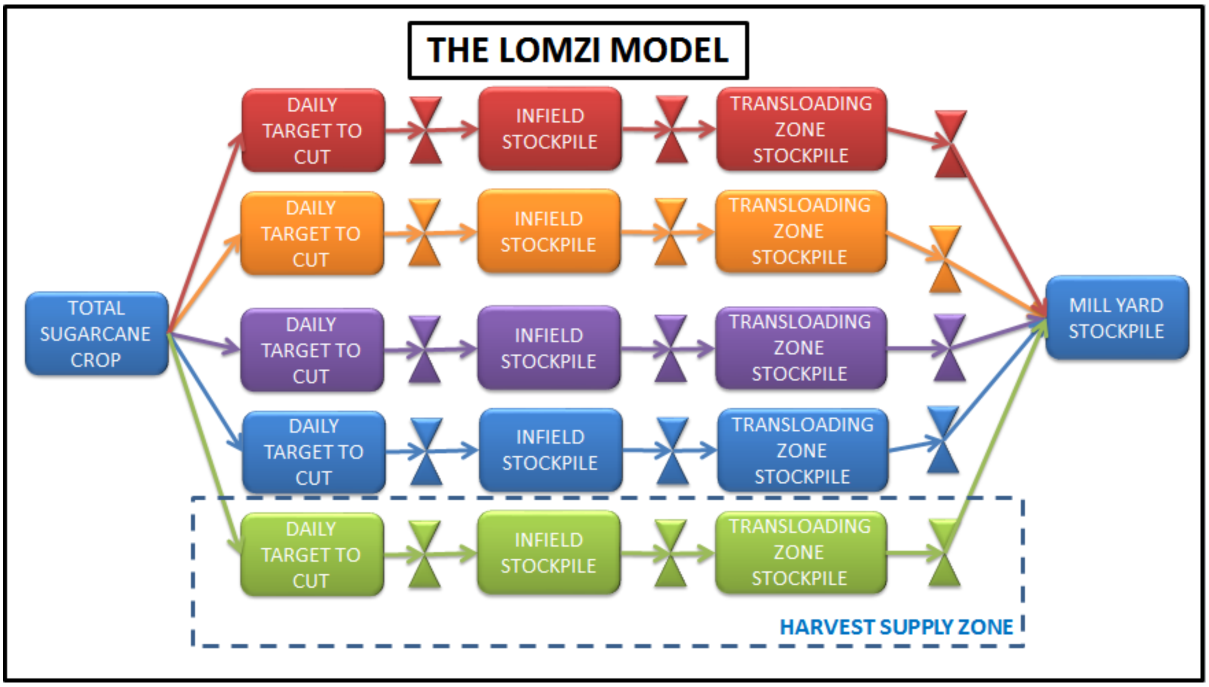


Figure 5.2 LOMZI structure, when applied to a MSA

For each harvest zone the daily cutting, extraction and transport capabilities are simulated. The tons of sugarcane that are cut, extracted and transported to the mill are recorded for each zone. In this way the model mimics the real-life situation where different harvesting fronts within a MSA contribute to the total cane delivered to the mill. An overall sugarcane budget for the mill area is recorded by the model. The budget displays which days are in the planned season and this determines when the model begins to simulate harvesting. The tons of cane left to cut for the whole mill area is shown. Daily totals of cane cut, extracted and transported for the whole MSA are recorded. A record of the daily mill stockpile size is also displayed.

The simulated actual length of the milling season is determined when the total crop for the mill area has been harvested or when a different user-determined threshold is exceeded, such as a certain date, beyond which harvesting is undesirable. The 'actual' length of the milling season may be longer than the planned length of milling season, if the simulated cane supply to the mill is below the daily delivery targets that were planned. This could be due to the interaction of different factors that control cane supply. The days in the 'actual' season are recorded in the sugarcane budget.

LOMZI was programmed in Microsoft Excel. In the model, each row represents a day of the harvest season. For each harvest zone, individual spread sheets are used to model the weather, crop size and harvesting capabilities for each day. The easy-to-modify structure of LOMZI can allow various other topics of the sugarcane supply chain to be investigated, apart from the actual length of milling season, for example, how increased capacities may affect no cane stops.

5.2 Modelling the Weather

Rainfall and temperature form the core of the factors that drive the length of the harvest season. They control crop growth, yield and quality (Inman-Bamber, 1994a; Singels *et al.,* 2012). They also influence the supply chain in many other ways, such as determining which days are conducive to harvesting (Hildebrand, 1998; Weekes, 2004; Higgins and Davies, 2005; Rangel *et al.*, 2010; Boote *et al.,* 2011; Kadwa, 2012). The need for realistic daily rainfall and temperature data to drive processes within LOMZI led to the inclusion of a weather generator based on the ClimGen Model (Stöckle *et al.,* 2001; McKague *et al.,* 2003; Safeeq and Fares, 2011). Because modelling the weather falls out of scope of this study, only a brief description of the ClimGen method is included below, as well as references for further investigation, if necessary.

A weather generator is a computer model that generates complete, synthetic daily climate data for a particular location, based on historic weather data (McKague *et al.,* 2003).The ClimGen weather generator was chosen because it is user-friendly and can be applied to any location in the world, where sufficient weather data exist to parameterise the model (Stöckle *et al.,* 2001; McKague *et al.,* 2003). ClimGen has also been shown to perform reasonably well at a wide range of different locations (Stöckle *et al.,* 2001; McKague *et al.,* 2003). The ClimGen model has the potential to generate values for daily precipitation, maximum and minimum temperatures, relative humidity, solar radiation and wind speed, if daily series of these variables are available (Stöckle *et al.,* 2001; Safeeq and Fares, 2011). The relationships between the generated variables are maintained and output follows seasonal patterns (Stöckle *et al.,* 2001). Values for temperatures are produced from a continuous multivariate stochastic process. Daily means and standard deviations for this process are conditioned by the dry or wet state of the day. Wet and dry days are generated by a first order Markov Chain. Values for precipitation are generated using a Weibull distribution (Stöckle *et al.,* 2001; McKague *et al.,* 2003; Safeeq and Fares, 2011).

The potential for the spatial and temporal variation of weather in a MSA has been documented (Muchow *et al.,* 1998b). However, in-depth modelling of a particular sugar mill area and the possible differences in weather between harvesting zones fall beyond the focus of this study. For this reason, the weather generator was used to simulate only one weather data set to be used in all ten harvesting zones of the generic model.

5.3 Modelling Crop Size and the Planned Season Length

The amount of sugarcane to be harvested from a MSA varies from season to season and is driven primarily by the weather and, to a lesser extent, by management and economic factors (Singels *et al.,* 2003). In LOMZI, crop size is generated according to historical crop sizes for the mill area. A beta distribution was used to represent crop size because of its versatility.

In the MSAs of South Africa, Mill Group Boards use estimates from growers and historical mill crushing data to plan the length of the milling season (Hildebrand, 1998; Gaucher *et al.,* 2004; Schorn *et al.,* 2005). It is up to individual MGBs to follow specific rules and guidelines to plan when the season will start and end. For example, the MGB might avoid crushing before Easter, because growers may be unwilling to harvest over this time. A discussion with the MGB of a MSA will facilitate the programming of these ‘rules’ into the model.

In LOMZI, the total crop size for the mill area, divided by a historical daily mill throughput, is used to calculate the estimated season length, in days. Historical daily mill throughput should be determined from mill crush data and discussions with mill management. In the generic model, the average mill throughput value was assumed to be 300 tons per hour, with an overall time efficiency of 0.8.

In the model, each day of the year is assigned a harvest suitability rating to rank each day, according to the rules followed by the MGB. The most desirable day of the year to harvest is ranked first, the next most desirable day is ranked second, and so on, until the least desirable day is ranked 365th. Harvesting is then simulated on all the days that have ranking values below the number of days in the estimated season length.

5.4 Modelling Cane Supply to the Sugar Mill

This section covers the specifics of modelling cutting capability, extraction capability and transport capability in LOMZI. A section discussing stockpiling in LOMZI is also included.

5.4.1 Cutting capability

The following approach in LOMZI represents cutting capability. For each harvesting zone, there is a certain maximum cutting capacity (in tons) for any day, which is influenced by semi-stochastic processes that represent various issues, such as labour absenteeism and the weather. These factors need to be determined for each MSA during the modelling process, and then calibrated for the model. The actual tons of cane cut on each day of the harvest season in LOMZI is taken as the minimum between the daily cutting capability and the target of cane to be cut in the harvest zone. When LOMZI is applied to a real-life situation, the cutting capability for each harvest zone would need to be determined through discussions with farmers, mill management and by examining available mill delivery data.

Growers base their cutting capability on their Daily Rateable Deliveries (DRDs), assigned to them by the Mill Group Boards and the cutting techniques that they employ on their farms (Le Gal *et al.,* 2004). By adjusting the amount of labour, equipment and operational practices employed, growers can alter their maximum harvesting capacities (Le Gal *et al.,* 2004). Le Gal *et al.* (2004) found that large-scale growers have significant extra harvesting capacity, up to double of what is required, because this accommodates times when it is more difficult to meet DRDs. Based on this, it was assumed in the generic version of LOMZI that the maximum cutting capability is double of what is required on average. However, it must be noted that Le Gal *et al.* (2004) combined cutting capability and extraction capability under the term harvest capability.

5.4.2 Extraction capability

In a similar manner to harvest capability, LOMZI assumes that for each harvesting zone there is a maximum extraction capability (in tons) for any day. This maximum extraction capability is then reduced by stochastic factors, calibrated for the MSA. For example, a rainfall event hampers the extraction of cane from fields and thus, when the weather generator simulates rain, the extraction capability for that day is reduced. In LOMZI, the actual tonnage of cane extracted on each day is taken as either the daily extraction capability or the amount of cane available in the in-field stockpile, whichever is smaller.

The South African sugarcane supply chain has a tendency to be over-capitalised (Bezuidenhout, 2010). Based on the findings of Le Gal *et al.* (2004) and the explanation for cutting capability, the extraction capability for the generic model was assumed to be, on average, double what is required.

5.4.3 Transport capability

In LOMZI, transport capability is modelled in the same manner as cutting and extraction. It is assumed that for each harvesting zone there is a maximum transport capability available on any day. The actual daily transport capability is determined by multiplying the maximum transport capability with semi-stochastic factors that represent real-world issues. These could include breakdowns, industrial action or adverse weather conditions, any of which may hamper the transport of sugarcane to the mill. The most important driving factors of transport for each MSA must be determined and then programmed into LOMZI. The simulated weight of cane transported each day by the model is taken as the smaller of either transport capability or the amount of cane available for transport on that day.

The transport arrangements in place at a mill area are of particular interest. Le Gal *et al.* (2004) explain that some MSAs have a central contractor who handles all, or most of, the cane transport. In other areas, several contractors handle the bulk of transport, while in other cases most of the cane is delivered by individual growers. Often there is a large mix of transport arrangements. The generic LOMZI structure needs to be adapted to mimic the transport arrangements found in a specific MSA.

Le Gal *et al.* (2004) found that, for a particular mill area in South Africa, transport capacity was between 1.25 and 1.5 times greater than what was required to meet DRDs. Results from a study by Giles *et al.* (2005) also suggested that unnecessary transport capacity exists in South African sugar supply chains. This is due to individual growers owning their own transport equipment and a lack of sugarcane transport co-ordination. For these reasons, it was assumed in the generic LOMZI that transport capacity is 1.5 times greater than the amount required on average.

Some cane is lost to road-side losses while being transported to the mill (Loubser, 2002), however, in the generic model this was assumed to be negligible. If it is determined that road-side losses are a significant problem in a specific MSA, LOMZI could be adapted to represent this situation.

5.4.4 Stockpiling in the sugar supply chain

Bezuidenhout (2010) describes the stockpiles found in a typical South African sugarcane supply chain. In LOMZI, stockpiling in-field, on loading zones and at the sugar mill is accounted for. The stockpiles are represented as a weight (tons) of cane at each point. Because the model runs on a daily time step, there is no indication of how stockpiles may vary during the course of the day. The model simply records what was left in the stockpile from the previous day, what weight of cane is added on a specific day and what is removed from the stockpile for that day. In essence, the stockpile levels recorded by LOMZI represent a snapshot of the stockpile at the end of a particular day.

The option to use stockpile size as a controlling factor for harvest operations in LOMZI exists. For example, the model could stop simulating cutting on a particular day, if the in-field stockpile exceeds a certain threshold. These relationships will be unique for individual MSAs.

5.5 Modelling Sugarcane Quality

The sugarcane quality model described in Chapters 3 and 4 was inserted into LOMZI. The daily average quality of sugarcane arriving at the sugar mill is predicted for the MSA being modelled. Weather inputs to the quality model are generated by the LOMZI weather generator. The quality model coefficients and limits must be calibrated separately for the MSA under question, before LOMZI can be used to simulate milling seasons. As LOMZI currently stands, sugarcane quality is not simulated for each harvest supply zone, but for the mill area as a whole.

6. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

6.1 Conclusions

The length of the milling season has important implications for sugarcane supply chain efficiency and profitability. Many interrelated factors must be accounted for when determining the acceptability of a certain length of milling season. These include, but are not limited to, sugarcane quality, milling capacity, harvesting capacity, transport capacity, social issues, such as labour absenteeism, and even the politics between growers and millers. Each mill area is unique and a customised solution to the length of milling season question is required. All stakeholders in a sugarcane supply chain need to collaborate to ensure that the correct season length is implemented.

This study assumed that the daily average quality of sugarcane delivered to a mill could be simulated with an acceptable degree of accuracy, by utilizing recent rainfall and temperature data. The sugarcane quality model uses readily-available quality and weather data, collected by the sugar industry, to predict daily average brix %, pol % and fibre % of sugarcane delivered to a mill. The preceding 11 weeks of weather data is used by the model to predict daily cane quality. The model was verified on independent data and achieved R^2 values of between 0.56 and 0.74. This level of accuracy was achieved with average rainfall and temperature data for the mill areas where the model was applied, namely Umfolozi and Sezela. It is expected that the quality model's performance could be improved with better aggregation of weather data, which could provide a more accurate picture of MSA weather conditions. The option exists to use Excel Solver to calibrate a weighting factor for each weather station.

Excel Solver proved a valuable tool to develop this type of model. Mathematical optimisation and an understanding of how sugarcane reacts to water and temperature allowed the study to make sense of historical mill data. As far as the author is aware, this is the first time that quality at a mill area scale has been simulated in this way.

The quality model was able to predict brix % and pol % cane better than fibre % cane. In general, the model over-predicts lower quality values and under-predicts higher values (as seen in Figures 4.1, 4.2 and 4.11). It is interesting to refer to Table 4.8, which shows the reductions in model performance when certain sections of the model are switched off. For brix % and pol %, longer-term rainfall (1 – 10 weeks in the past) was the greatest determinate of quality. Recent rainfall (Week 0) was more important for modelling the fibre % of cane. At Umfolozi, heat units played the largest role in determining fibre % cane, but were unimportant at Sezela. Unlike at Felixton, Umfolozi and Sezela showed little responses that were associated with the day of the week. The day-of-the-week adjustments could be removed from the model with little impact. However, some interesting weekly trends of cane quality were observed by examining these adjustments.

The quality model calibrated a wide range of effective rainfall limits and base temperatures (Table 4.3). At Umfolozi, rainfall limits were calibrated between 4.28 mm and 57.90 mm and base temperatures between 0°C and 21.35°C. For Sezela, the quality model calibrated rainfall limits between 0.01 mm and 62.98 mm and base temperatures between 0.56°C and 29.74°C. The wide spread of limits can be partly explained by the MSA scale of weather data used to calibrate the quality model, especially at Sezela. It was expected that the daily rainfall limits (PF_{max}) would be smaller than the weekly rainfall limits (P_{max}). This proved to be correct for all but pol % cane at Umfolozi and fibre % cane at Sezela. However, PF_{max} and P_{max} are very small for fibre % cane at Sezela.

An especially interesting and unexpected output of the quality model is that an average cut-to-crush delay may be estimated by studying the daily rainfall coefficients for fibre % cane after calibration at a MSA. The Umfolozi rainfall coefficients showed a clear increase in magnitude on Day 2, which possibly indicates that the average delay between cutting and crushing is two days. This is a reasonably short delay. The daily coefficients at Sezela for fibre % cane showed a less marked, but still clear, increase on Day 2.

The sugarcane quality model was inserted into LOMZI, a sugarcane supply chain modelling framework. Part of the work of this study was to adapt LOMZI to allow any mill area in South Africa to be modelled, with the aim of facilitating length of milling season decisions. Because LOMZI is easy to adapt, there is the potential to examine a wide range of other sugarcane supply chain issues, besides the length of the milling season. For example, the impact of reducing no-cane stops or mill breakdowns on mill throughput. LOMZI was refined to accommodate a wider range of mill area dynamics than before. In the updated version of LOMZI, a mill area can be represented by up to 10 harvest supply zones. The climatic, cutting, extraction and transport characteristics of each zone can be modelled. The weather and the size of the crop to be cut are stochastically determined for each zone. The quality model was successfully integrated into LOMZI to provide daily mill area average brix %, pol % and fibre % cane values.

6.2 Recommendations for Future Research

Possible areas for future research include:

- An investigation into the inclusion of upper and lower limits for effective rainfall and heat units in the quality model. Initial investigations into adding lower limits for effective rainfall resulted in negligible improvement in the quality model's performance, but there may be benefits to conducting further research into more sophisticated rainfall and temperature limits to the model.
- Recoverable Value (RV) is an industry measure of the quality of sugarcane, which is understood by all stakeholders in South African sugarcane supply chains. The quality indicators predicted by the quality model can be used to calculate RV. Future research could investigate using the quality model to simulate RV and compare this to other methods of RV prediction currently in use by the sugar industry.
- The quality model simulates the general trend of sugarcane quality satisfactorily, but often fails to account for times when sharp increases or decreases in the quality of sugarcane are recorded at the mill. This indicates that other factors, besides rainfall and temperature, may influence quality at times. Future research could aim to improve the model's performance when this occurs.
- Using weather data at a MSA scale, the quality model performed better at Umfolozi than at Sezela, most likely due to the concentration of the main growing areas. Further research could assess methods to better represent the climatic conditions of a MSA, which should result in better predictions of quality.

- Insufficient data exist to calibrate the quality model for conditions before deterioration has taken place. Future research could study ways of quantifying the level of deterioration, or predicting the quality before deterioration occurs. No reliable and universal method of predicting deterioration currently exists.
- The modelling approach that was developed in this study could be useful in many other areas of bio-resources production, for example, in fruit production. Further research could adapt the method to suit a wide variety of applications.
- Several additional supply chain components need to be researched and included in LOMZI. These include a model of the sugar mill and an economics component.
- The sugar industry collects vast amounts of information. Future research could examine ways of analysing industry data to produce valuable inputs for LOMZI. This work could improve the calibration of LOMZI for a MSA and make it easier to apply.
- Future work on LOMZI could cover the inclusion of downstream processes to the model, as these may have large impacts on the ideal LOMS. This could include ethanol production or the co-generation of electricity.
- Further development of LOMZI is needed to build in feedback loops to the supply chain. For example, stockpile levels could determine when simulated cutting is suspended.
- Most importantly, future research should deal with the application of LOMZI for a specific MSA, to assess its ability to aid LOMS decisions.

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