ISSUES PERTAINING TO CANE SUPPLY RELIABILITY AND STOCKPILING AT THE UMFOLOZI SUGAR MILL – MODEL DEVELOPMENT AND APPLICATION

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ABSTRACT

The co-owned Umfolozi Mill area has developed as an integrated supply chain. Cane supply reliability was identified as a potential area for productivity improvement at Umfolozi. It is important that the cane supply to a sugar mill arrives at a steady and reliable rate. A reliable cane supply ensures that the mill can operate at an optimum efficiency. Sugarcane supply reliability depends on how the mill area adapts to unforeseeable changes in the supply chain. An important aspect to this is the weather and how it affects the harvesting regimes. The sugarcane supply chain at Umfolozi is divided into two branches, road transport and tram transport. The trams account for 70 % of the cane delivered to the mill and the can is sourced from a climatically homogenous region. In the occurrence of a rainfall event of above 5 mm, infield harvesting cannot take place on the Umfolozi Flats; hence 70 % of the mill"s supply is halted for one or more days. To address the problem, a stochastic model was created to simulate the effectiveness of an enlarged cane stockpile if it were maintained on the current tram sidings outside the mill and were crushed when wet weather prevented further harvesting. The stockpile was simulated on a first-in first-out principle and was able to supply the mill with enough cane to continue running for 24 hours. The model was then used to conduct a series of Monte Carlo simulations on which sensitivity analyses and economic feasibility assessments were carried out. Results show that the stockpile was effective in reducing the length of milling season and the number of no-cane stops. However, on further analysis into the implications of creating a stockpile it was found that 1% recoverable value (RV) was lost during the 24-hours that the cane is stored outside the mill. The loss in revenue as a result of the RV reduction had a negative impact on any savings created with the implementation of the stockpile. This result made apparent the negative impact of deterioration to the whole supply chain. Further research is required to determine more accurately the rate of deterioration, and therefore, quantify more accurately the losses that occur in the supply chain. A significant outcome of the study was the development of a mechanistic tool which drove decision making at Umfolozi Sugar Mill. It lead to the development of the modelling framework LOMZI, a simulations based framework which places more emphasis on environmental factors and risks.

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1. INTRODUCTION

Over the past decade the South African sugar industry has been under pressure to increase efficiency and hence profit margins, mainly as a result of the deregulation of the agriculture and food sector (Gaucher *et al.*, 2003). Added to this is the fact that sugar supply areas in South Africa have become less reactive to changes due to the silo optimisation (Gaucher *et al.*, 2003) and have not grown or are producing less sugar (Meyer and van Antwerpen, 2001). The sugar supply chain has been identified as an area through which increased gains can be realised. Increased gains are possible by improving the management of the cane supply to the mill in an integrated manner (Le Gal *et al.*, 2004).

The multi stakeholder environment in which the South African sugar industry operates provides a difficult environment for optimisation (Le Gal *et al.*, 2003). Stakeholders have optimised their own particular area of interest to the possible detriment of the whole system (Le Gal *et al.*, 2003). If the management of the supply chain is not efficient, the quantity and quality of cane that is delivered to the mill will be reduced, and therefore impacts negative on the quality of sugar produced (Le Gal *et al.*, 2003). To increase efficiency new measures that provide more flexibility and hence a better ability to adapt to change are required. Potential advancements to the sugar supply chain should be based on global solutions that have an overall positive effect on the sugar supply chain.

Seventy percent of the cane supply to the Umfolozi Sugar Mill is grown on the Umfolozi Flats. The flats are climatically homogeneous, experience a high water table and are comprised mainly of fine silt. The combination of these factors prevents infield harvesting after rainfall events resulting in low cane supply reliability and hence no-cane stops at the mill. It has been reported that this has a profound effect on the operation of the mill as well as on the length of milling season (LOMS). A modelling approach may help to assess the effect of creating a stockpile of cane outside the mill in order to reduce the frequency of no-cane stops. The model should take into account how the rainfall patterns vary over the season and its effect on LOMS.

There have been a number of researchers in South Africa who have developed models in order to optimise season length and simulate cane supply management for example Le Gal *et al.* (2003) and Wynne and Groom (2003). However, to the author‟s knowledge, a simulation model which takes into account how changes in rainfall affect the length of milling season (LOMS) has not been developed. The impact of rainfall on the cane supply reliability and length of milling season will be the focus of this research.

In order to unlock the potential in the supply of cane to the mill, tools are required that can capture the complexity of the system, and once created, stakeholders need to be able to review and discuss the potential changes (Muchow *et al.*, 2000). In addition, the relationship between the miller and grower must be the focus in order to improve the coordination and hence increase the reliability of the mill supply (Gaucher *et al.*, 2003). Simulation modelling allows for a more comprehensive understanding of how the supply chain operates, rather than supplying one optimised solution, provoking more discussion and negotiation amongst stakeholders (Hatchuel and Molet, 1986; de Geus, 1992; Le Gal *et al.*, 2003). In creating a simulation model a holistic view of the mill is obtained (Barnes *et al.*, 2000).

The aim of the study was not only to model the Umfolozi system but also to develop a comprehensive stochastic model which can be used to assess the impact of creating a stockpile of cane outside a mill. The first objective of the research, presented in Chapter 2, was to conduct a literature review on cane supply by tram systems and the cause and effect relationships experienced within a mill as a result of the harvesting conditions, no-cane stops and cane deterioration. Chapter 3 details the methodology behind the development of the modelling framework, named LOMZI. The results of the model are presented in Chapter 4. The final objective of the research was to analyse the results of the model. Chapter 5 details the final conclusions and impacts of the model.

This research did not attempt to optimise the number of tram trucks present in the model. The model also did not attempt to develop a new standard for length of milling season, it serves to highlight the impact of rainfall and how it affects on the milling season.

2. AN OVERVIEW OF CAUSE AND EFFECTS WITHIN TRAMWAY TRANSPORT SYSTEMS AND SUGAR MILL

In order to assess the effect of rainfall and no-cane stops on a sugar mill it is first necessary to briefly cover the method of cane transport to the mill. The literature review therefore begins with an overview of sugarcane tramways in South Africa. It then focuses on the effect of rainfall and no-cane stops on the processes in a sugar mill.

2.1 Sugarcane Tramway Systems

Tramways systems were first reported in the South African Sugar Journal in the 1920s (Warner, 1923). The reports mainly focused on the sharing of practical experience from sugar estates. In many of the reports the tram systems were praised as an extremely cheap form of transport (Anonymous, 1927; Palairet, 1932). There was a decrease in the use of tramways in the mid-1960s mainly as a result of increased cost of replacing tracks and rolling stock (Meyer, 2005). In many areas this would have been excessive, especially after flood damage. The Umfolozi Mill operates the last remaining tramways system.

2.1.1 Tramway layout

A well planned layout of tramways was essential to the optimum performance of the system (Warner, 1923; Anonymous, 1927). The gradient and radius of corners needed to be suitable for the size of engine and trucks used. A set of guidelines were developed for the planning of a tramway system (Warner, 1923; Palairet, 1932). If these guidelines have been followed during the planning stages the systems would have operate economically, efficiently and there would have been be a reduction in wear and tear (Anonymous, 1927).

The degree of investment in the system would have been based on the amount of cane that is to be moved (Warner, 1923). Like most transport system tramways are only economical when used at a maximum capacity. The extremely high capital cost of a tram system is dependent on the total length of the track required and the running cost of the total area served, however, it is almost completely independent of the total tons of cane handled (Palairet, 1932). Tramway systems are therefore only suited to areas of high yield.

Advantages of tramway systems as listed by Palairet (1932) are:

- Cane is only handled once
- The tram system is usually managed by the mill or company and therefore provides a greater opportunity for optimisation.
- Normal wet weather is not a retarding factor to the delivery of trucks. However, infield transport is still affected.

2.1.2 Tramway operation

The usual tramway system consists of a network of tramlines, tram trucks, locomotives, infield transport equipment, and specialised spiller configurations at the mill. The system components of tramway systems are relatively simple. However, the capital expenditure required for their implementation is extremely high (Meyer, 2005). Because of the complex network and delivery schedules, tramways are usually operated by the sugar mill or by a single company. Tram trucks are delivered each morning to fields where the individual growers take over loading. The number of trucks delivered is dependent on the daily rateable delivery for that particular grower.

Infield Loading

Infield loading is controlled by the individual grower. The mechanism of loading has changed during the past century. The first method was either to manually carry cane to the tram truck on the track or to construct temporary tracks into the field (Warner, 1923; Anonymous, 1927). In 1948 a new method of loading was devised. The method involved transporting the tram truck into the field by tractor from where it was directly loaded (Maclean, 1949). This method of loading is still used in Umfolozi, however, modifications to the trailer have been made and the cane is loaded mechanically. An example of the operation is shown in Figures 2.1 and 2.2.

Figure 2.1 Tram truck infield haulage

The system at Umfolozi uses a single or double piggy back tram truck trailer (Meyer, 2005). The trailer straddles the tramline and a section of track is angled down onto the tramline from the trailer. An empty tram truck is then winched onto the trailer which causes the section of track on the trailer to pivot to horizontal and settle on the trailer. A tractor transports the trailer into the field where it is loaded by mechanical means. Once full, the tram truck is transported back to the tramline where it is winched back down onto the track as seen in Figure 2.2.

Figure 2.2 Setting a loaded tram truck back onto the tram lines

2.2 Sugar Mill Systems

Processes within the sugar mills are fairly generic, normally only differing in the equipment used. Rein (2007) published a cane sugar engineering hand book, which comprehensively covers the production of sugar. This reference has been used throughout the literature review to introduce each process. Since this is purely an introduction, a review of the latest scientific publications concerning each process fell outside the scope of this review. The cause and effect relationships covered have been sourced from studies conducted mainly in South African sugar mills.

Rein (2007) introduces the first step in the production of raw sugar as the preparation of the cane stalk. This involves the washing of the cane, knifing and shredding to produce a cane fibre bed. The fibre bed is fed into either a diffuser or milling tandem. The aim of the diffuser or mill is to extract sucrose rich juice from the fibre bed with the least amount of impurities. The diffuser uses hot water to wash the sucrose from the fibre bed, while the milling tandems use pressure, as well as a relatively small amount of water to remove the sucrose. Diffused fibres exiting the diffuser are normally milled by rollers to squash out the remaining juice.

The juice extracted from the diffuser or milling tandem, most commonly termed raw juice, is passed through a clarifier. The clarifier removes unwanted substances from the raw juice, such as soil, cane fibre particles and impurities that contribute towards a darker raw sugar colour (Rein, 2007). The clarifier uses various flocculants, which collect unwanted particles causing them to settle to the bottom of the tank forming a mud (Rein, 2007). The solution that results from the clarifier is termed clear juice. Mud is a waste product and is passed through a press filter where excessive water is removed and where the remaining solids are usually returned to the fields as fertiliser (Engelbrecht *et al.*, 2009). An alternative to filtering mud is to pass it back into the diffuser, here the cane fibre acts as a filter (Rein, 2007).

Evaporation follows the clarification process. In the evaporation process the water content of the clear juice is reduced in order to form syrup (Rein, 2007). The syrup is then processed through three crystalliser pans, A, B and C, each pan crystallising lower quality syrup (Rein, 2007). With the addition of seed crystals to these pans, crystallisation occurs, thus growing the seed crystals (Rein, 2007). After evaporation in the pans, the resultant sugar crystals and clear juice, now termed massecuite, is mixed to obtain an even consistency and then passed through a centrifuge (Engelbrecht *et al.*, 2009). The centrifuge separates the sugar crystals from the remaining syrup or molasses, as it becomes known towards the end of the process. The crystals are then sent to drying and storage/packaging. The remaining syrup is passed to the next evaporation pan or passed out of the C pan as molasses (Engelbrecht *et al.*, 2009). The newly created sugar crystals are dried to ensure suitable properties for handling and to prevent degradation during storage (Rein, 2007).

The processes outlined above are shown in Figure 2.3. To the right of each process are the performance metrics for that process. In order not to clutter the diagram the only input and output to the system is sugarcane and dry raw sugar. Major outputs that have not been included are bagasse, filter cake, molasses and water.

Sugar mills have to deal with a wide variation in the quality and volume of flow of raw material. Variability in the sugarcane is as a result of the high number of role players in the upstream supply chain, as well as climatic variation.

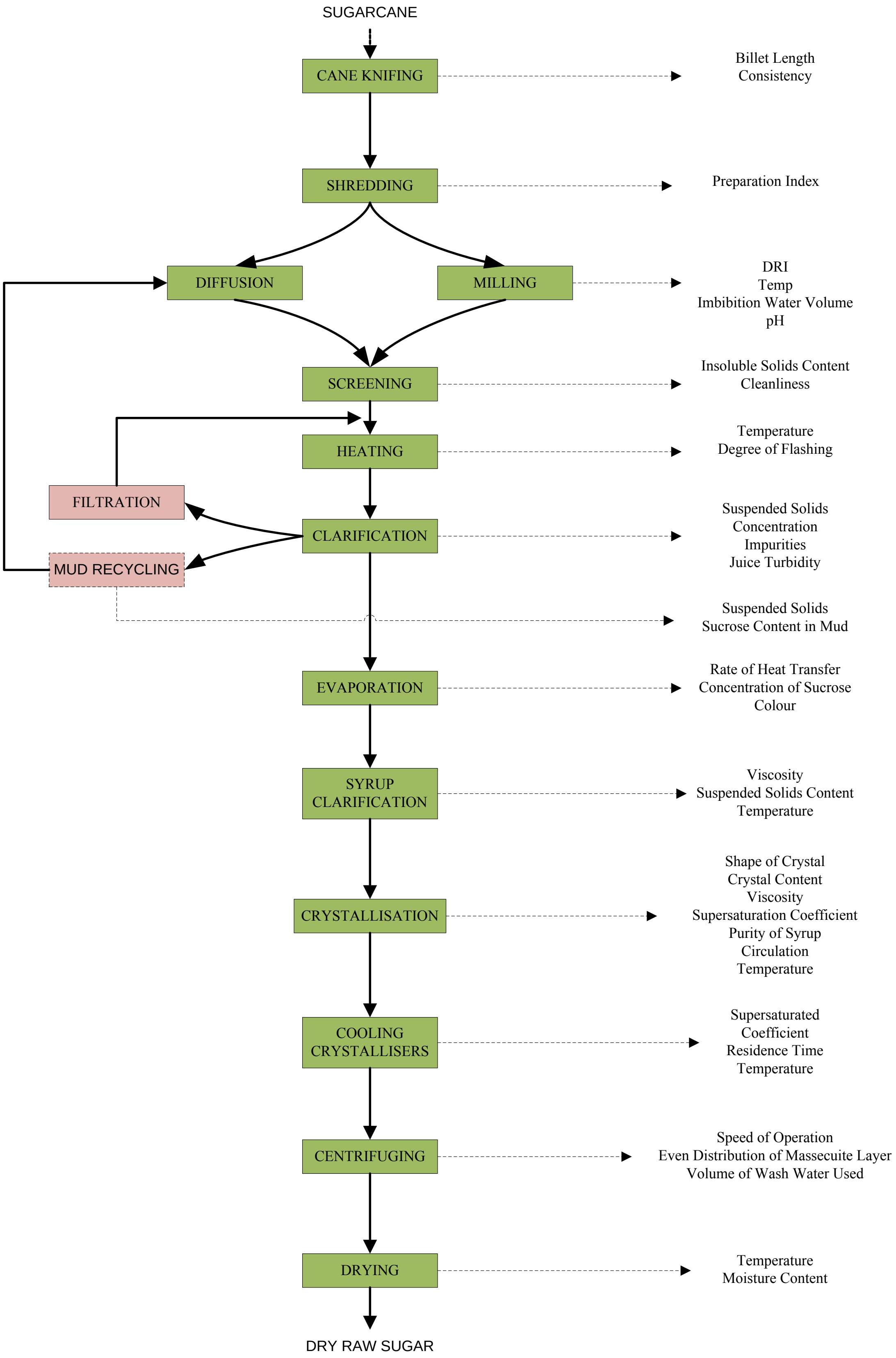

Figure 2.3 Generic steps of raw sugar production (after Engelbrecht *et al.*, 2009)

2.2.1 Input factors

There are a number of factors that affect the processes throughout the mill. The most important of these factors is cane quality and quantity. Without consistent and high quality cane, quality sugar cannot be produced.

The quality of the cane is partly affected by the delay between harvesting and crushing (Barnes *et al.*, 1998), also, the method of harvesting (Meyer *et al.*, 2002), cane variety (Barker and Davis, 2005) and the time of year during which the cane is harvested affect quality (Smits and Blunt, 1976; Barker and Davis, 2005). For example, an increase in the delay of transferring the harvested cane to the mill increases the loss of sucrose, as well as the build up of impurities in the cane stalk (Reid and Lionnet, 1989; Ravno and Purchase, 2005). The prevailing climatic conditions exacerbate the losses and build up of impurities (Reid and Lionnet, 1989). During the warm wet summer months, deterioration rates are higher compared to winter months (Ravno and Purchase, 2005). The purity of the sugarcane crop changes as the season progresses (Lonsdale and Gosnell, 1976). Lonsdale and Grosnell (1976) found that purity is lowest in the beginning of the season *i.e.* March, and increases in July after which it is fairly constant until December. Eggleston and Harper (2006) found that mannitol, formed by the bacterial degradation of sugarcane, is a good indicator of harvest to crush delay related cane quality.

Dextran is formed from the breakdown of sucrose as a result of bacterial action, thus important factors that control its formation are temperature, moisture and residence time (Ravno and Purchase, 2005). The formation of dextran is also increased when mechanical chopper harvesting is undertaken due the increased surface area and exposure of the cane ends to contamination (Ravno and Purchase, 2005).

If the cane has not been completely burnt, it has been reported that the dextran content increases (Simpson and Davis, 1998). Dextran creates a number of problems throughout the sugar mill, as well as within the subsequent refinery. The dextran also forms a sticky residue to which soil particles attach, contributing to the soil entering the mill (Simpson and Davis, 1998). Simpson and Davis (1998) suggest that high soil content will cause excessively high levels of mud. This in turn causes insoluble calcium phosphate, a suspended solid, to be carried over into the clear juice, resulting in poor quality sugar (Simpson and Davis, 1998). Soil can also increase the wear and tear on the hammer mill and shredders.

2.2.2 Output requirements

Raw sugar can be consumed directly, however, it is usually processed further in a sugar refinery. The sugar mill is therefore, required to produce a raw sugar quality that meets the expectations of the refiner. Sugar quality is measured according to a variety of factors namely, pol, colour, ash, insoluble solids, filterability, dextran, starch, reducing sugars and grain size/distribution (Rein, 2007). All of the above affect the cost and ease of refining.

In South Africa raw sugars are divided into three quality groups. The groups are classified according to the parameters mentioned above. Table 2.1 contains the values with which the raw sugar qualities are analysed. Payments for raw sugar are based on the pol value of the raw sugar. In addition to this there are bonuses and penalties for the various characteristics of the sugar (Rein, 2007).

Table 2.1 Analysis for grades of sugar in South Africa (after Rein, 2007)

Property	**Very High Pol (VHP)**	**High Pol (HP)**	**Low Pol (LP)**
Pol in °Z	99.3	98.9	97.8
Moisture in g / 100 g	0.10	0.24	0.35
Reducing Sugars in g / 100 g	0.16	0.50	1.10
Ash in g / 100 g	0.15	0.17	0.20
Colour in IU	1500	1800	2200
Starch in mg / kg	110	110	110
Dextran in mg / kg	90	90	90

2.3 Juice Extraction

Sugarcane is delivered to the mill as either complete stalks or billeted into shorter pieces (Engelbrecht *et al.*, 2009). The cane undergoes three processes before bagasse and raw juice are produced, namely cane knifing, shredding, and milling or diffusion (Engelbrecht *et al.*, 2009). The purpose of juice extraction is to rupture as many cane plant cells as possible and then to separate the soluble from the insoluble particles (Payne, 1968; Moor, 1994).

2.3.1 Cane knifing

If not already billeted, as a result of mechanical chopper harvesting, cane knifing involves the reduction in size of the cane stalk into small billeted pieces (Rein, 2007). Cane knifing prepares the stalks into an even bed that will ensure a stable flow of cane into the shredder without blockages (Ried, 1994). Ried (1994) reports that the tip velocity of the knives affects the quality of the preparation. The knifing of the cane should not cause an excessive reduction in fibre length as this would impede diffusion (Reid, 1995). Longer fibre lengths ensure that the fibre bed in the diffuser is loosely packed, allowing for higher percolation rates (Reid, 1995). The concerns with the cane knifes are wearing and damage due to excessive soil, rocks and foreign objects, such as metal chains in the incoming cane (Ried, 1994). There is an increase in the amount of soil entering the mill during rainy weather (Ried, 1994). Following knifing, the billeted cane is fed into the shredder, which serves to rupture the cell walls of the cane stalk.

2.3.2 Shredding

Shredding is achieved by feeding the billeted cane from the knifing process through a series of hammers, which shred the billets into a fine bed of fibre (Moor, 1994). It involves the extensive destruction of the cell walls of the cane stalk (Reid, 1995). Complete destruction of the cell ensures a high extraction rate in the diffuser (Payne, 1968; Moor, 1994). In the report of cane shredding, Moor (1994) states that cane should not be over prepared as it leads to “pulping” of the fibre. Pulping causes difficulties in the transfer of fibre through the mill and leads to decreased percolation rates in the diffuser (Moor, 1994). The shredder is also susceptible to wear and tear as a result of soil, rocks and foreign objects. A damaged shredder will decrease the preparation index contributing to poor extraction (Smits and Blunt, 1976).

The shredding of billeted cane stalks was previously measured using the Preparation Index (PI), the amount of sucrose which can be washed from the cane relative to the total quantity of sucrose present, measured as a percentage (Loubser and Gooch, 2004). The new method to measure the preparation of cane is called the Diffusion Rate Index (DRI). The DRI is a measure of the time taken to remove a certain Brix from the shredded cane sample (Loubser and Gooch, 2004); therefore, it is a measure of how easily Brix can be removed rather than how many cane cells are open as in the PI method (Loubser and Gooch, 2004). Brix is the measure of dissolved solids in sugar, juice, liquor or syrup using a refractometer in units of °Bx (Rein, 2007). For example, in the case of a pure sugar-water solution of 25°Bx there is 1 part sugar to 3 parts water.

2.3.3 Milling

Milling uses pressure to expel the fluids from the fibre bed (Engelbrecht *et al.*, 2009). Milling is no longer a popular method of extraction in sugar mills, with only 9% of sugarcane in South Africa processed by milling (Lionnet *et al.*, 2005). Milling is not severely affected by no-cane stops due to the relatively short residence time of cane fibre in the milling tandem.

2.3.4 Diffusion

The diffuser is the more common method of extraction of sucrose from the cane fibre and has largely replaced milling (Reid, 1995). Soluble particles are washed out of the cane by a counter-current leaching process (Rein and Woodburn, 1974). The amount of soil, degree of cane preparation, bulk fibre density and pH of the percolating liquid has an effect on the diffuser efficiency (Lionnet *et al.*, 2005). These factors contribute to the rate at which percolation takes place.

Poor percolation results in flooding, hence a decrease in extraction (Lionnet *et al.*, 2005). Operational problems concerning flooding include overflow of fibre out of the feed or discharge ends of the diffuser and spilling cane juice (Lionnet *et al.*, 2005). Mitigation of the problems results in downtime and hence a reduction in the volume of cane processed (Lionnet *et al.*, 2005). Flooding can be avoided by decreasing the throughput and imbibition of the diffuser, *i.e.* allowing more time for percolation (Rama *et al.*, 2006). Rama *et al.* (2006) also suggest removing suspended solids from the cane bed to ensure efficient permeability especially during high ash loads.

High loads of suspended solids enter the mill with the cane as a result of high soil loads. This usually occurs during rainy weather, especially when there is a delay between harvest and milling, allowing the dextran "glue" to accumulate soil (Simpson and Davis, 1998). High clay content soil has the most effect on the percolation rate (Lionnet *et al.*, 2005). In experiments conducted by Lionnet *et al.* (2005), and confirmed by Rama *et al.* (2006), it was found that the impermeable nature of clay prevented the free flow of imbibition water through the samples.

Liming in the diffuser is undertaken to maintain high pH imbibition water in order to (a) reduce the silica levels in the clear juice, (b) limit corrosion and (c) reduce inversion (Walthew *et al.*, 1998). Inversion is the changing of sucrose to glucose and fructose (Rein, 2007). Reducing silica levels helps prevent scale build up in the evaporators (Walthew *et al.*, 1998). Liming, however, may also reduce the permeability of the cane bed (Lionnet *et al.*, 2005). If poor quality lime is used, such as lime containing extra silica, the positive effect of a high pH will not be realised (Lionnet and Walthew, 2004). At a high pH both silica and Brix will continue to be leached from the cane fibre; however, the rate at which Brix is leached will decrease more rapidly than that of silica (Walthew *et al.*, 1998). This is more significant if the pH of the solution is above 8.5 (Lionnet and Walthew, 2004). Silica is not easily removed during clarification (Walthew *et al.*, 1998).

Temperature affects the rate of sucrose extraction in the diffuser. Reid (1995) suggests that temperatures should be maintained above 75°C in order to attain high extraction rates. The average temperature of the diffuser should be maintained at 85°C (Reid, 1995). High temperatures result in an increase in the juice colour (Reid, 1995). For example, Reid (1995) reports that at the Amatikulu Mill a 10°C drop in temperature resulted in a 25% reduction in colour. Diffusion results in raw sugar of higher colour, but lower impurities than that of milling, depending on the temperature of the diffuser (Reid, 1995). According to Reid (1995) raw sugar colour from a diffuser is on average about 25% higher than sugar from a milling tandem. This may be a disadvantage when the goal is to produce a low colour sugar, or when milling a white sugar (Reid, 1995). The main benefit of the diffuser is the fact that the starch is removed from the raw juice as a result of the high temperatures (Reid, 1995). The higher temperature denatures the starch allowing enzymes to further break the starch down (Reid, 1995).

In diffusers the measurement of microbiological breakdown is possible. The organism, *hyperthermophiles,* is responsible for the breakdown of sucrose to lactic acid (Reid, 1995). The lactic acid content in the diffuser is measureable, and is a relationship that exists between the sucrose lost and the lactic acid produced (Reid, 1995). For every part of lactic acid formed there is a resultant two parts sucrose loss, as well as a drop in juice purity (Reid, 1995). Cane fibre that is left in the diffuser is prone to microbiological breakdown. The start up and shut down of diffusers are, therefore, a cause of concern in a sugar mill (Reid, 1995). If the stops last for over six hours it is advisable to clear the cane fibre in the diffuser to prevent the degradation of the sugar (Reid, 1995).

2.4 Energy Production and Consumption

Sugar mills have the potential to produce enough energy to operate without input from external sources. However, there are factors that change the amount and quality of fuel supplied to the boilers, as well as the efficiency of the boilers.

The energy in a sugar mill is supplied mainly by the burning of bagasse, the waste product of sucrose extraction. The bagasse is fed into the boilers where it is burned for steam and electrical energy production (Rein, 2007). Energy is required at all stages within the mill, even when the processing of cane has ceased. Therefore, there is a requirement to store excess bagasse or to have an alternative source of energy, such as coal (Ried, 2006).

The quantity and quality of the bagasse affects the amount of energy that is available for steam production. The quantity of the bagasse is measured by the fibre content of the cane, while the quality is measured by the calorific value and combustion efficiency (Ried, 2006). The calorific value of bagasse is not significantly affected by the amount of fibre, pith, cane stalks and cane tops (Don and Mellet, 1977). Ried (2006) states that the most important factor concerning the calorific value and combustion efficiency of the bagasse is the amount of moisture remaining after sucrose extraction. The moisture of the bagasse is controlled at the dewatering mill, if the moisture content rises to above 55%, additional alternative fuel needs to be added, often in the form of coal (Ried, 2006). Alternative fuel may also need to be added if the ash percentage in the bagasse rises above 5% (Ried, 2006).

In order to achieve a higher degree of extraction the quantity of imbibition water used in the diffuser and mill tandem may be increased (Rein, 2007). An increase in imbibition water dilutes the raw juice, and therefore, more energy is required to evaporate the additional water. A further addition of water occurs in the vacuum pan to maintain and control the growth of crystals and in the centrifuge to wash the crystals of syrup (Ried, 2006). Both these processes place a further demand on energy for evaporation (Ried, 2006). In the case of poor syrup quality as a result of poor cane quality an increase in the amount of water may be required (Ried, 2006).

The boiler converts the by-product from sugar extraction, bagasse, to steam and electrical energy for use in the sugar mill. The operation and maintenance of the boiler is affected by the quality of the incoming fuel, which in most cases is bagasse, and the quality of the boiler feed water. Sand in the bagasse, more typical of diffusers, can result in wear in the boilers (Reid, 1995).

The quality of the feed water to the boiler affects the operation and maintenance of the boiler (Reid and Dunsmore, 1991). Sucrose is identified as a great cause of boiler problems. Reid and Dunsmore (1991) report that if sucrose contamination occurs at a concentration more than 200 ppm operational problems within the boiler can be expected. At high temperatures the sucrose breaks down into organic acids. These lower the pH of the feed water causing an increase in the conductivity resulting in corrosion (Reid and Dunsmore, 1991). To correct the low pH caustic soda can be added to the feed water to bring the pH back to the required 11.0. Dosing with caustic soda however is not desired and it can increase the total dissolved solids (Reid and Dunsmore, 1991).

Sucrose causes damage to the boiler components which leads to costly repairs and boiler downtime. Some examples of damage and problems as listed by Reid and Dunsmore (1991) are foaming, carry-over and fouling of strainers, steam traps, control valves and turbine blades. Carbonaceous deposits can also form on the boiler drum and heating surfaces, which reduces heat transfer and may cause blockages or corrosion (Reid and Dunsmore, 1991). Sucrose concentrations of 20 ppm are deemed as being safe provided the chemical treatment of feed water is adequate (Reid and Dunsmore, 1991).

The chemical treatment of the water aids in the control of deposits and scaling of insoluble compounds in the boilers (Cuddihy *et al.*, 2005). The deposit and scaling are as a result of a decreasing solubility of the deposit forming salts with increasing temperature and concentration (Cuddihy *et al.*, 2005).

2.5 Juice Clarification

Juice clarification reduces the number of insoluble particles in the raw juice resulting in a clear juice ready for crystallisation. This step in the sugar mill involves the removal of bagacillo from the raw juice, heating of the juice and lastly the removal of suspended particles from the raw juice. Clarification produces a clear juice and a waste product termed mud. The mud can be reworked to extract any remaining sucrose.

2.5.1 Screening

Screening is required to remove the larger insoluble solids from the raw juice after the diffuser or milling tandem (Meadows, 1996; Rein, 2007). The remaining smaller particles are removed through clarification (Rein, 2007). Screening is relatively unaffected by no-cane stops and deterioration, however, if high loads of soil enter the mill the screen may experience increased wear (Meadows, 1996).

2.5.2 Heating

The purpose of heating is to bring the temperature of the raw juice slightly above 100°C to allow for effective flashing prior to clarification (Meadows, 1996). Flashing removes air particles attached to the non-soluble particles, and therefore enhances the rate of settling in the clarification tanks (Meadows, 1996). The heating process is required to increase the temperature of the raw juice from ambient temperature, if a milling tandem is used, or from 60 ˚C in the case of a diffuser (Rein, 2007). Once the juice has reached the required temperature it is flashed in a flash tank to remove trapped air and to ensure a constant temperature juice to the clarifier (Rein, 2007).

An operational problem associated with heat exchangers is the build up of scale on the inside of tubes or on the plates and can constitute a significant resistance to heat transfer within a few days (Rein, 2007). This scaling is very similar to that encountered in the evaporators as discussed in Sections 2.6.1 and 2.6.4. A major cause of increased scaling is an increase in the silica content of the raw juice. Increased silica in the raw juice is mainly as a result of an increase in the amount of sand that enters the sugar mill (Rein, 1990). Rein (1990) reports in a study at Felixton Mill that the increase in sand entering the mill was attributed to stale cane as a result of delays due to the rain. Tests conducted by James *et al.* (1978) show that the scaling results in a reduction in the heat transfer coefficient and, therefore, an increase in the time to heat the raw juice to the required temperature.

2.5.3 Clarification

The most common method of clarification in sugar mills today is defecation. This involves the addition of lime as a flocculant to the raw juice, which forms flocs that trap suspended matter. As the particles gain mass they settle as mud to the bottom of the tank where it can be drained out. The mud is filtered or passed back to the diffuser in order to extract more sucrose. This process is described in Section 2.5.4. The purpose of clarification is to remove suspended matter and to provide a clear juice of minimum turbidity, colour and low calcium content. The main cause of suspended matter is cane containing high loads of soil. This is more prevalent when harvesting in wet conditions after a no-cane stop or when deterioration is high as a result of a long burn to crush delay. The filterability of raw melt in the sugar refinery after the production of a raw sugar may be affected by the impurities remaining in the sugar after clarification (Mkhize, 2003). This is mainly due to the high loads of suspended solids and turbidity (Mkhize, 2003). The frequent start up and shut down of the mill, often as a result of no-cane stops, can also cause high turbidity problems. This becomes more of a problem towards the end of the season when the supply of cane to the mill is unsteady (Mkhize, 2003). The effects of inconsistent operation of the mill on the clear juice could last a couple of hours.

During clarification there is a possibility of mud carryover. Carryover can contain fine suspended matter from the clarifier. Dextran as a result of deterioration in the raw juice has been identified as the cause of the fine suspended matter (Ravno and Purchase, 2005). The dextran acts a protective colloid and inhibits coagulation, therefore preventing the entrapment of fine matter in the mud (Ravno and Purchase, 2005). The fine matter has an effect on the quality of the sugar, increasing the ash content and increasing its colour (Ravno and Purchase, 2005).

2.5.4 Filtration

Rein (2007) states that the mud from the clarifier still contains a certain amount of raw juice. In order to recover the juice the mud is passed through a filtering system. Bagacillo, fine bagasse particles, are added to the mud from the clarifier aiding in the mud filtration. The bagacillo is added in the mud mixture to optimise permeability of the pressed mud, which is now termed filter cake. Ideal conditions for permeability are at temperatures above 75 ˚C and at pH levels slightly below 8.5. The filtrate from the process is returned to the raw juice from the diffuser or mill.

2.6 Juice Evaporation and Crystallisation

The most important process in the sugar mill is the removal of large amounts of water and the subsequent crystallisation of the sucrose. The quality of the final sugar crystal is affected by the method of crystallisation, the stage at which the crystal is formed and the impurities present in the syrup. Before crystallisation can take place the clear juice must first be reduced to form syrup and clarified once more using floatation.

2.6.1 Evaporation

In order to produce a syrup ready for crystallisation a substantial amount of water must be evaporated from the clear juice. The evaporation process reduces the water content of the clear juice to a concentration of 65 to 68% dissolved solids, forming a substance called syrup (Rein, 2007). This is just below the crystallisation point of syrup, thus enabling storage in liquid state (Rein, 2007). Evaporation is undertaken in multiple effect evaporators using steam as the energy source (Rein, 2007). Most of the energy produced from the boilers is used in evaporation. The efficiency of the process therefore, has a profound effect on the overall energy efficiency of the mill and vice versa, energy problems will first affect the evaporation stage (Rein, 2007). Optimum performance is achieved when the steam supply to the evaporators is constant, ensuring steady operation (Rein, 2007). In addition to a constant steady operation the physical level of juice inside the tubes should be 25 to 50% of the maximum height which produces optimum circulation and heat transfer in the evaporator (Rein, 2007).

At high temperatures the reducing sugars that are present in the clear juice can easily affect the colour of the resultant sugar. The increase in colour is more pronounced when high viscosity syrup is processed (Rein, 2007). It is, therefore, more desirable to have a lower temperature profile across the evaporators and to heat the high viscosity syrup at the lowest temperature (Rein, 2007). For this reason cocurrent flow of the clear juice and steam is used in the sugar industry (Rein, 2007). Cocurrent flow through the evaporator also reduces the residence time of the dissolved solids, thus minimising the time for degradation of the sucrose (Rein, 2007).

Scale in evaporators affects the heat transfer and hence the efficiency of the evaporator (Rein, 2007). A major component of scale is silica, which is deposited as the Brix increases across the evaporator train and pans (Walthew *et al.*, 1998). The amount of silica present in the clear juice is determined by the quality of cane entering the mill and the pH of the imbibition water used in the diffuser (Walthew *et al.*, 1998). In this case the poor quality cane is often as a result of harvesting cane during, or too soon after, a rainfall event which increases the soil load entering the mill.

2.6.2 Condensers and vacuum equipment

Rein (2007) states that condensers and vacuum equipment are required to condense water vapour produced from the evaporators. To induce cooling the vapour from the evaporators comes into direct contact with the cooling water. Common types of condensers are the countercurrent multi-tray condenser and rain type condensers. An alternative is the multi-jet condenser, which injects a fine mist of water into the flow of the warm vapour. The difference in temperature between the vapour and the cooling water determines the amount of cooling water required. The vacuum equipment is used to remove the incondensable gases from the condensers. In order to reduce the temperature of the cooling water spray ponds or cooling towers are used to reject the heat to the atmosphere. The efficiency of this process is generally not directly influenced by no-cane stops or deteriorated cane.

2.6.3 Syrup clarification

Syrup clarification is usually required when producing sugar for direct consumption after the sugar mill. Rein (2007) states that syrup clarification reduces the suspended solids content, hence the colour of the final sugar crystals. Syrup clarification uses clarification by floatation. Floatation clarification is preferred because the high viscosity of the syrup does not allow for clarification by settlement (Rein, 2007). Syrup clarification involves the addition of a polyacrylamide flocculant followed by the aeration of the syrup (Rein, 2007). Other chemicals such as sulphates or phosphates can be added to achieve a certain sugar quality (Rein, 2007). The flocculant causes the suspended particles to combine allowing the fine air bubbles to carry these particles to the surface of the clarifier. The layer of scum that forms on the top of the clarifier is continuously removed while clear syrup is drained off the bottom of the clarifier. The temperature of the syrup affects the efficiency at which the suspended solids are removed. It is suggested that there are improvements in the removal of suspended solids up to a temperature of 85 ˚C (Rein and Cox, 1987). Syrup clarification reduces the final viscosity of the molasses by about 25% (Rein and Cox, 1987). The reduced viscosity allows for higher Brix massecuite and the use of less steam and water on the centrifuges (Rein and Cox, 1987). However, deteriorated cane as a result of no-cane stops may increase the viscosities and negatively affect the process. If the impurities are not removed from the syrup they will obstruct the development of high quality crystals.

2.6.4 Crystallisation

Crystallisation of sucrose occurs when the sugar solution becomes supersaturated. The objective of crystallisation is to bring the syrup into the supersaturated state and control it at a specific concentration to achieve a steady rate of crystallisation (Rein, 2007).

Crystallisation of the sugar solution usually takes place by passing the solution through three pans, each pan crystallising a lower grade of syrup or massecuite as the substance becomes known when it contain fluid and crystals. The degree of crystallisation that can take place in the pan is dependent on the viscosity of the massecuite and its ability to flow out the pan (Rein, 2007). Before the massecuite becomes too solid it is drained out of the pan and is centrifuged to separate the sugar crystals from the remaining massecuite. The remaining massecuite is fed into the next pan. This process it repeated again until a final molasses is produced. The number of steps required to achieve final molasses is dependent on the purity of the syrup (Rein, 2007). A no-cane stop increases the impurities present in the syrup. The impurities increase the viscosity of the massecuite and therefore reduce the time that the sucrose can remain in the crystalliser. The sucrose that did not crystallise may be lost to the molasses.

2.7 Cooling Crystallisers

Rein (2007) describes that cooling crystallisers are designed to maximise crystallisation after passing through the crystallising pans. The massecuite that leaves the vacuum pan is supersaturated and hot, hence further crystallisation can be induced by cooling. Cooling crystallisation is undertaken prior to centrifuging in either batch or continuous crystallisers. It is preferable to operate a continuous cooling crystalliser as it requires less labour and automation. The massecuite is cooled by coils through which cooling water is passed. The operational objectives during cooling crystallisation are to ensure the required residence time and target temperature on leaving the crystalliser are achieved. The correct outlet temperature of the massecuite is attained by controlling the rate of flow of cooling water through the cooling pipes.

Problems may occur in the cooling crystalliser if the Brix of the solution is high, or the massecuite is cooled down further than normal as a result of mill breakdowns or particularly cold weather (Rein, 2007). Lower than normal temperature results in a massecuite that is too viscous for the operation of the mixing drives. A solution to the problem is to either increase the temperature of the cooling water or to blend molasses into the cooling crystallisers (Rein, 2007). No-cane stops will affect the energy available to this process and necessitate the burning of a substitute fuel, such as coal, to prevent the crystallisers from becoming dysfunctional.

2.8 Centrifuging

Centrifuging separates the liquid also known as molasses from the crystals after crystallisation. It utilises a centrifugal force, which drives out the molasses from between the sugar crystals. Rein (2007) states that additional wash water can be added to the centrifuge to remove the remaining liquid from the crystals.

As discussed in Section 2.6.4 the presence of dextran and other impurities in the raw juice causes deformation of the sugar crystals. This makes them susceptible to breaking during centrifuging and the subsequent blockage of the screens (Smits and Blunt, 1976). In the event of a no-cane stop the degree of deterioration increases. As a result, the amount of dextran in the processing stream is increased, therefore, reducing the quality of the sugar crystal.

2.9 Drying

The drying of the raw sugar is the last process in the sugar mill before it is sold to the market or to the sugar refinery. Drying is required to ensure free flowing characteristics are obtained for handling purposes and to meet customer specifications (Rein, 2007). In addition to attaining the physical properties required by the customer, drying is also required to prevent sucrose loss as a result of microbiological or chemical degradation (Rein, 2007).

2.10 Discussion and Conclusions

This literature review has highlighted the link between the quality of cane that is delivered to the mill and the profound effect on the quality of raw sugar that is produced. It has also highlighted the importance of consistent cane supply in order to ensure stabilised milling processes.

In the case of the Umfolozi Sugar Mill, a majority of the cane is sourced from the Umfolozi Flats. The ability to harvest on the flats is sensitive to rainfall which disrupts the cane supply. In addition to this the cane that is delivered after a rainfall is often deteriorated and of poor quality containing large amounts of soil. The literature review has shown that with inconsistent cane volumes there is a build up of impurities in the mill which reduces the quality of the raw sugar produced. There is also an increase in the operational costs of the mill. In summary the mill is affected by no-cane stops and deterioration in the following ways:

- Increased quantities of soil in the cane which results in increases wear, predominately in the shredders and boilers.
- Sand reduces the rate of percolation in the diffuser, increasing the risk of flooding and reducing the diffuser efficiency.
- Sand also increases the silica content of the raw juice resulting in more scale in the evaporation processes, reducing efficiency.
- The start-up and shut-down of the mill increases the risk of deterioration within the mill.
- There is often a need for an alternative energy source as a result of the disruption to the supply of bagasse to the boilers.
- Deterioration produces dextran which develops a sticky residue on the cane stalk and therefore transports more soil into the mill.
- Deterioration produces impurities which hinder the formation of sugar crystals.
- The viscosity of the syrup is increased thus requiring more water and energy for crystal formation.

Considering the effect of no-cane stops and deterioration on a sugar mill it was decided that this would be the focus of the study. In the case of Umfolozi this involves mitigating the effect of rainfall on the Umfolozi Flats. Although this literature review went into detail pertaining to milling, the model development will, to a larger extent aggregate these issues and combine them with supply chain dynamics.

3. METHODOLOGY – MODEL DEVELOPMENT, ASSUMPTIONS AND DATA ANALYSIS

The literature review outlined the need for a sugar mill to operate at a constant rate and process sugarcane of a consistent quality. A constant and reliable cane supply is attained by managing different sectors in the cane supply area to ensure growers are harvesting at a constant rate, thus having an equal share of the peak recoverable value (RV) period or compensated if the harvesting occurs early or late in the season (Le Gal *et al.*, 2004). A factor that affects the constant supply of cane to the sugar mill on a large scale is the prevailing weather systems. Rainfall prevents infield mobility, the ability to burn and increases the amount of sand contained in the harvested cane. This has a detrimental effect on the quality of raw sugar produced and the operating costs of a sugar mill. In order to reduce the negative effect of a rainfall event a counter measure is needed which can be implemented when harvesting is affected.

3.1 Umfolozi Mill and LOMZI

The Umfolozi Mill area is particularly susceptible to rainfall events. Cane in the Umfolozi sugar mill is supplied mainly by the Umfolozi Flats. The flats are a densely-farmed and highly-productive area of land on the flood plains of the Umfolozi River. While the remainder of the mill"s cane supply is sourced from areas relatively remote in relation to the flats and can, therefore, be assumed to experience different weather conditions. The Umfolozi Flats are prone to wet conditions because of the type of soils, topography and high water table. Harvesting is therefore inhibited even after a small amount of rainfall (McGrath, 2010).

Stakeholder discussions and analysis of the Umfolozi Mill area revealed that no-cane stops occur too frequently as a result of rainfall. To ensure that there is sufficient cane for the mill to continue operating a stockpile of cane could be created. The stockpile would typically be crushed when there is insufficient cane supply to the mill after a rainstorm.

A stochastic model, named LOMZI, was created in order to evaluate the potential effect of a stockpile outside the mill. The name LOMZI is derived from a combination of its potential effect on the LOMS and the area in which it was developed. The model was based on a daily time step with variable rainfall records as the main driver. A series of assumptions have been used in the case of insufficient data or when the system became too complex to model stochastically. These assumptions are discussed in this chapter.

LOMZI was created in Microsoft Excel® with the use of pivot tables and basic programming to run simulations. It consists of an input sheet where all the aspects that affect the delivery and quantity of cane outside a mill are taken into consideration. These are summarised in Figure 3.1 and are listed as in the model in Appendix B. The inputs to the model are processed within the model sheet using a line of formulae to represent each day in the season. A summary line from the model sheet is transferred to the output sheet after each season. Basic programming is used to simulate the specified number of seasons. In order to ensure that the model did not produce unrealistic outcomes the most conservative assumptions were maintained at all times.

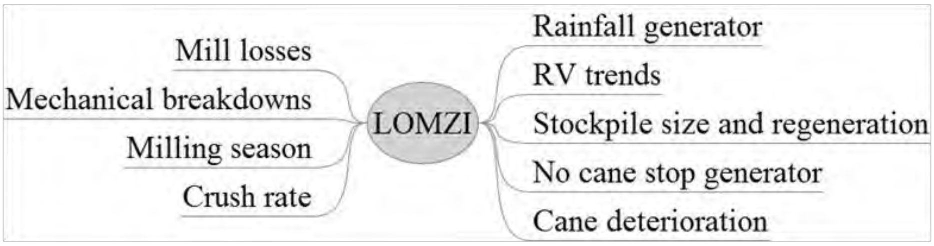

Figure 3.1 Factors considered in the LOMZI model at Umfolozi Mill

The entire Umfolozi Flats is serviced by a tramway system. A perspective view of the mill and the tram sidings is supplied in Figure 3.3. The photo is taken in the off season hence all the tram trucks are currently in the sidings. These sidings will be used to store the cane stockpile. An orthophoto of the Umfolozi Sugar Mill has been provided in Figure 3.2. The extent of the Umfolozi Flats has been marked out and the approximate position of the Umfolozi Land Owners Association (ULOA) Rainfall Station is shown.

Figure 3.2 Orthophoto of the Umfolozi Sugar Mill with an insert of the tram siding where the stockpile is to be created.

Figure 3.3 Umfolozi Sugar Mill and tram sidings where the stockpile will be created.

3.2 Rainfall receiver operating characteristics analysis

Receiver Operating Characteristics (ROC) analysis (Fawcett, 2006) was used to calibrate the depth of rainfall that leads to wet field conditions and hence no-cane stops. ROC analysis has been used in signal detection theory to determine the trade-off between correct predictions and false alarms (Fawcett, 2006). The results from the model are analysed using a confusion matrix in order to create a ROC graph which indicates visually how well the model predicts a certain outcome (Fawcett, 2006). Using these criteria, three seasons were analysed to determine the most appropriate set of limits, for example, whether 15 mm of rain will prevent harvesting for one or two days. The ROC analysis of the four different scenarios is shown in Table 3.1.

Table 3.1 Rainfall limit (*p*) categories used to correlate rainfall with no-cane stops at Umfolozi

Rainfall	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
1 wet day	$5\text{mm} \leq p <$ 20 mm	$5\text{mm} \leq p <$ 20 mm	$5\text{mm} \leq p <$ 15 mm	$5\text{mm} \leq p <$ 10 mm
2 wet days	$20\text{mm} \leq p$	$20\text{mm} \leq p <$ 30 mm	$15\text{mm} \leq p <$ 30 mm	$10\text{mm} \leq p <$ 30 mm
3 wet days	-	$30\text{ mm} \leq p$	$30\text{ mm} \leq p$	$30\text{ mm} \leq p$

The four scenarios are plotted on the ROC graph in Figure 3.4. Points closest to the top left corner are considered a better prediction of the actual circumstance *i.e.* a true positive rate of one and a false positive rate of zero. It was concluded that Scenario 4 (Table 3.1) was representative of the real situation.

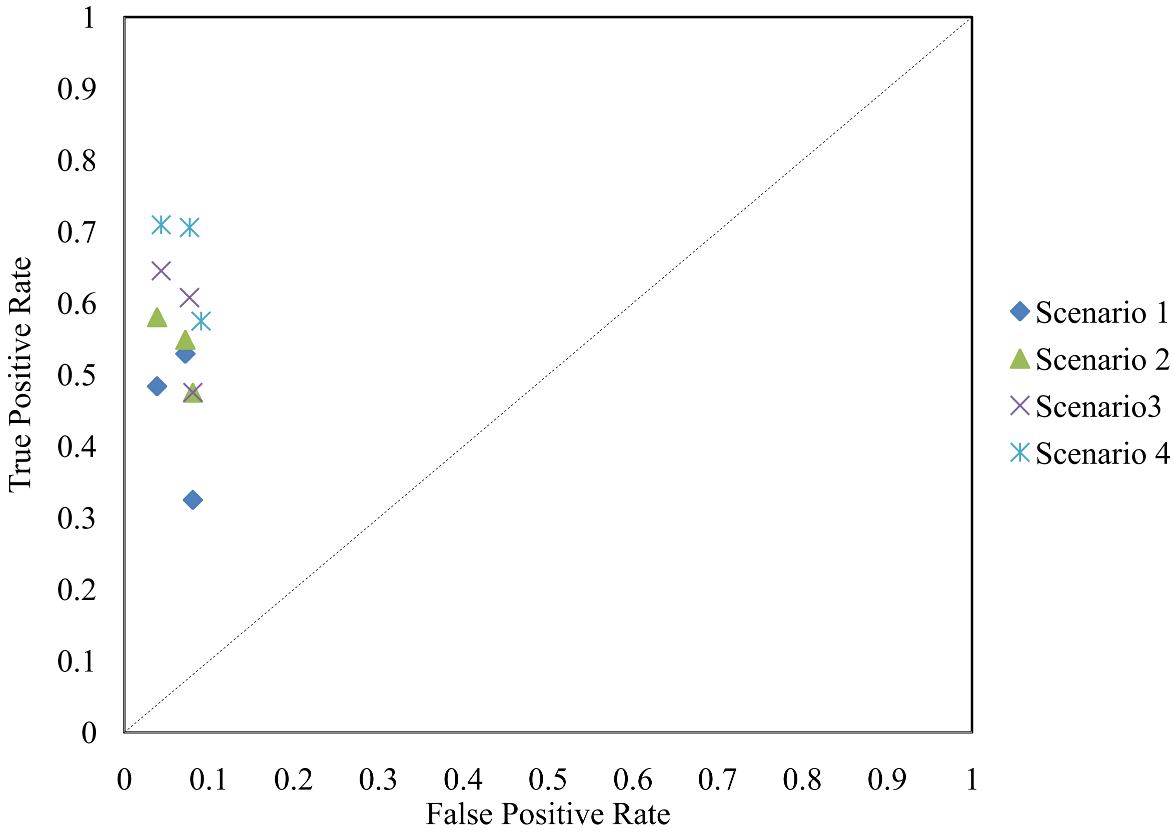

Figure 3.4 ROC graph used to determine the most suitable rainfall limits that indicate wet field conditions at Umfolozi

A rainfall generator was based on a Markov chain, which generates the probability of multiday rainfall events. The Markov chain works on the principle that once a rainfall event has taken place, the probability of rainfall recurring the following day changes (James and Caskey, 1963). The probability may increase or decrease, depending on the type of rainfall that occurs in the region during different times of the year. In the case of Umfolozi, for the majority of the season, there was a lower probability for multiday rainfall events than single day events. Figure 3.5 depicts the probability for a rainfall event, given that the previous day was dry (P_{dry}), and the probability for a rainfall event, given that the previous day was wet (P_{wet}). These values were derived from the 50 year rainfall data set at ULOA. The graphs show two short periods (in February and October) when multiday rainfall event were more likely. The probabilities of different amounts of rainfall were used to develop the rainfall generator. Multi-day rainfall events were of higher concern because of their effect on the supply of cane. It can be argued that during the early summer months there was a need to have two days of cane on hand or that the mill may need to shut down for a few weeks.

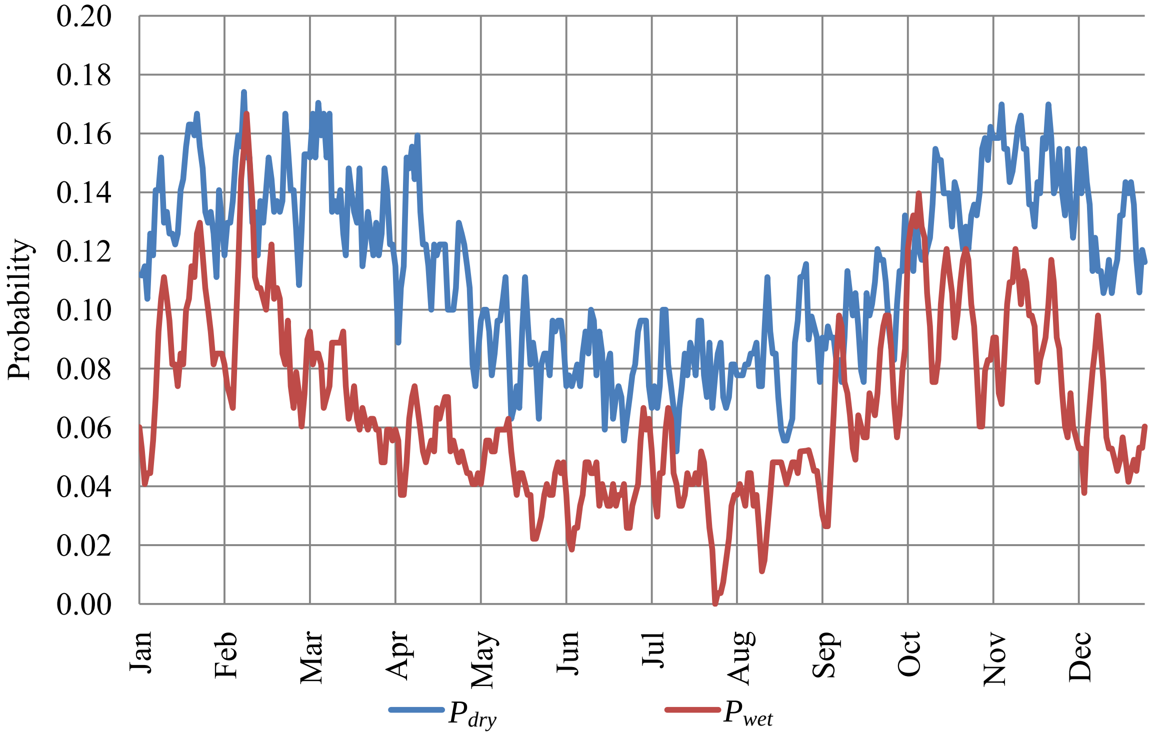

Figure 3.5 Markov probabilities for the Umfolozi Land Owners Association rainfall station

Rainfall was the main driver of no-cane stops, thus it was the basis on which the model was developed. Rainfall data were obtained from the SASRI weather web page (http://portal.sasa.org.za/weatherweb). Station 151, ULOA (28°29'0" S, 32°17'0" E) was assumed representative of the Umfolozi Flats, based on its centrality. The position of the rainfall station was marked on the orthophoto in Figure 3.2. The station had uninterrupted daily rainfall records for 53 years. These rainfall records were used to calibrate a stochastic rainfall generator as described below.

The first step in the development of a rainfall generator was to determine whether it rained on a particular day. For example using Figure 3.5, if on the 30th of April it did not rain, the probability of rainfall (P_{dry}) on the 1st of May would be approximately 0.10. A random number between zero and one was then generated. If this number was below 0.10 a rainfall event occurred. The second step was to determine the amount of rainfall that would occur. A second random number between zero and one was generated and compared to the probability limits as seen in Figure 3.6. For the 1st of May, if the number was between 0.00 and 0.20 then less than 5 mm of rain fell on that day. If the random number was between 0.20 and 0.53 then the amount of rainfall that fell was between 5 mm and 10 mm. If the random number was between 0.53 and 0.86 then the amount of rainfall that fell was between 10 mm and 30 mm. Finally, if the random number was between 0.86 and 1.00 then the amount of rainfall that fell was above 30 mm. From Figure 3.5, the probability to determine if it rains on the 2nd of May (P_{wet}) then changes to 0.04. Therefore if the random number was below 0.04 it would have rained for 2 days. The rainfall amount probabilities (Figure 3.6) are used again to determine the amount of rainfall that can be expected on the second day of rain.

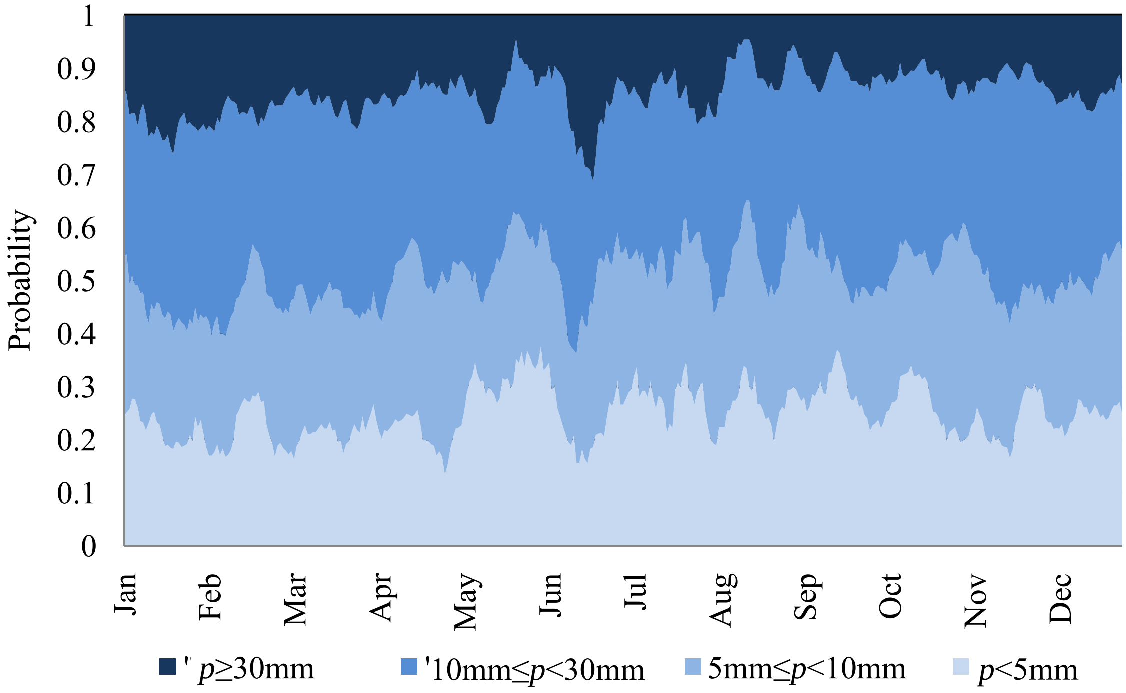

Figure 3.6 Rainfall depth probability *i.e.* the type of rainfall that can be expected during the season

3.3 Mill Mechanical Breakdowns

In order to accurately model the mill activity during the season, it was necessary to simulate random mechanical mill breakdowns. The reason for the frequent breakdowns was mainly as a result of a lack of maintenance. During the previous ownership little effort was made to maintain the mill. Breakdowns are similar to no-cane mill stops; however, the effect of a mill breakdown is more severe because of its unpredictability. Management therefore cannot go through the same procedures of shutting down the mill as they would when they were expecting a no-cane stop. Without the correct shutdown procedures, it can be expected that the losses during start-up and shut-down will be higher compared to no-cane stops (Table 3.4).

Mill breakdowns result in an increase in the length of the milling season. In order to factor in the effect of an unpredicted mill breakdown, historic data were analysed in an attempt to determine the frequency at which the mill experienced breakdowns. Over the period 2007 – 2009 the mill experienced breakdowns on 64% of the days in operation. The basic statistics from the mill stop data are summarised in Table 3.2.

Table 3.2 Basic statistics of mill mechanical mill stop data at Umfolozi

Statistic	**Value**
Number of mill breakdowns	591
Breakdown frequency	64%
Minimum duration	0.05 hours
Maximum duration	24 hours
Mean duration	4.128 hours
Variance in duration	23.199
Coefficient of variance	1.167

The first step in creating a mill breakdown generator was to determine whether a breakdown would occur on a particular day. On each day a random number between zero and one was generated. If the number was less than 0.64 a mill breakdown would be assumed. If so, the second step was to determine the length of the mill breakdown. The duration of each breakdown ranged from 0.05 hours to 24 hours. A β-distribution function was fitted to the breakdown duration data, as depicted in Figure 3.7. The β-distribution function was used to calculate the duration of the mill stop based on the parameters obtained from the β-distribution curve in Figure 3.7.

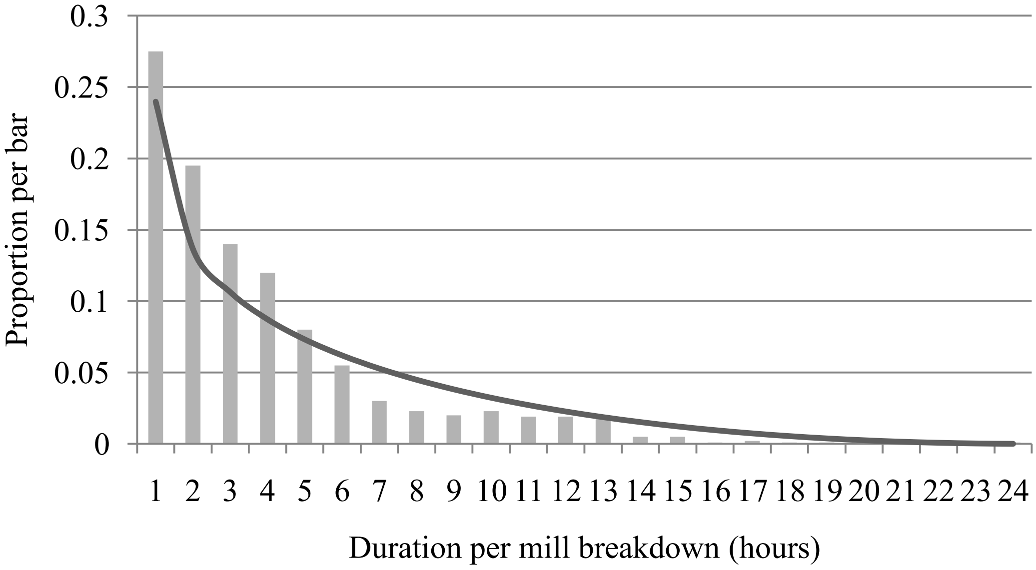

Figure 3.7 Distribution of mill breakdown data from the previous three seasons

3.4 Mill Crush Rate

Data supplied by the mill show that the mill crush rate was constantly adjusted in an attempt to maintain a flow of cane through the mill. For example, if management knows that there has been a problem with the tram system, the mill is set at the slowest possible rate until supply is back to normal. The previous three seasons were analysed to determine the maximum, minimum and average hourly crush rates. The mill‟s crush rate can vary from 152 $t.hr^{-1}$ to 407 $t.hr^{-1}$. The average crush rate of the mill over the past three seasons was 298 $t.hr^{-1}$. Table 3.3 summarises the past three seasons‟ crush rates in more detail.

Table 3.3 Average, maximum and minimum hourly crush rates ($t.hr^{-1}$) for the seasons 2007 – 2009 at Umfolozi Mill

	2007	**2008**	**2009**	**Overall Average**
Average	289	313	291	298
Maximum	418	390	412	407
Minimum	135	193	125	152

In the model, it was conservatively assumed that the crush rate varies between a minimum crush rate of 83 $t.hr^{-1}$ and an average crush rate of 220 $t.hr^{-1}$, limited by how much cane was available *i.e.* the mill cannot run faster to „catch up" lost time (Williamson, 2010). The production manager stipulated a minimum crush rate of 83 $t.hr^{-1}$ for the mill to continue running (Williamson, 2010). In the model the average crush rate was calculated by determining the rate required for the mill to crush the seasons" predicted tonnage of cane within the standard LOMS, without the implementation of a stockpile. According to the data available from the past five seasons, the mill generally opened in the second week of April and closed around the 23rd – 24th of December. This equates to an approximate season length of 260 days. In order to achieve a LOMS of 260 days the average crush rate in the model was set to 220 $t.hr^{-1}$.

3.5 Stockpile Size and Rate of Replenishment

The Umfolozi Mill does not currently maintain a substantial stockpile. It was decided that the stockpile in the model should be able to keep the mill running for an additional 24-hours. Thus, during a no-cane stop the stockpile should be capable of mitigating 5 mm – 10 mm rainfall events. The size of the stockpile was therefore set to 3696 tons (70% x 24 hr x 220 $t.hr^{-1}$) – one days worth of cane from the Umfolozi Flats.

During simulations, the rate of replenishment of the stockpile was assumed to be constant at 10% of the total stockpile *i.e.* 369.6 tons of cane was added to the stockpile every day. While maintaining first-in first-out principle the stockpile would achieve maximum capacity after 10 days. The assumption that the harvesting teams would be able to increase their capacity by 10% was confirmed by the tram system manager.

3.6 Cost of No-cane Stops

A no-cane stop occurs when there is insufficient cane for the mill to continue crushing. The processes in the sugar mill require a constant flow of material to operate at an optimum. A no-cane stop prevents the constant supply of cane to the mill, creating inefficiencies and increasing the cost of sugar production. Another factor that required consideration was cane deterioration and contamination. For example, if cane remains in the diffuser for prolonged periods of time, non-sucrose contaminants such as dextran develop. This affects the quality of the sugar crystal development.

In order to estimate the typical cost of a no-cane stop at the Umfolozi Mill, contact was made with the mill production manager. The main costs of a no-cane stop constitute the cost of coal and the liquidation cost. During a stop the mill can burn up to 100 tons of coal, 50 tons during shut-down and 50 tons during start-up (Williamson, 2010). In addition to the coal, there was approximately 10 tons of sugar that was lost as a result of liquidation. During the development of the model, the cost of coal was set at R 710 per ton and sugar losses were equated to R 4 400 per ton. The total cost of a mill stop, start up and shut down, was calculated to be R 115 000. Table 3.4 gives a summary of the components and cost of the no-cane mill stop. The table was used to determine the cost of each mill stop and summed over the entire milling season.

Table 3.4 Summary of no-cane stop costs

Component	**Quantity (tons)**	**Cost per ton (Rand per annum)**	**Component Cost (Rand per annum)**
Coal	100	710	71 000
Liquidation Losses	10	4 400	44 000
		Total	**115 000**

3.7 Recoverable Value (RV) Data Input

Average daily RV values were generated for each day of the milling season. RV attempts to account for the effect that cane quality has on sucrose recovery, and therefore, provide a more accurate estimate of the real value of the cane supplied to the mill (Peacock and Schorn, 2002). RV data from the mill were available in weekly averages and were interpolated into daily averages in order to suit the daily stochastic model. The average weekly data over the past four seasons were plotted and a 6th order polynomial curve was fitted to the data. The fit was sufficiently representative with an R^2 value of 0.977. Figure 3.8 depicts the four season averaged weekly RV data, as well as the polynomial curve. The 6th order polynomial equation was used to determine daily values throughout the milling season from 17th April to 26th December.

In order for the model to accommodate for a season which would extend beyond the 26th of December and for which historic data were not available, a binomial curve was assumed between the last week of the milling season and the first week of the milling season. The binomial was selected on an assumption of the RV values based on the recommendations of a sugarcane modeling specialist (Bezuidenhout, 2011). A minimum value for the curve was set at an RV of 8%. The resulting polynomial and binomial combination are shown in Figure 3.8.

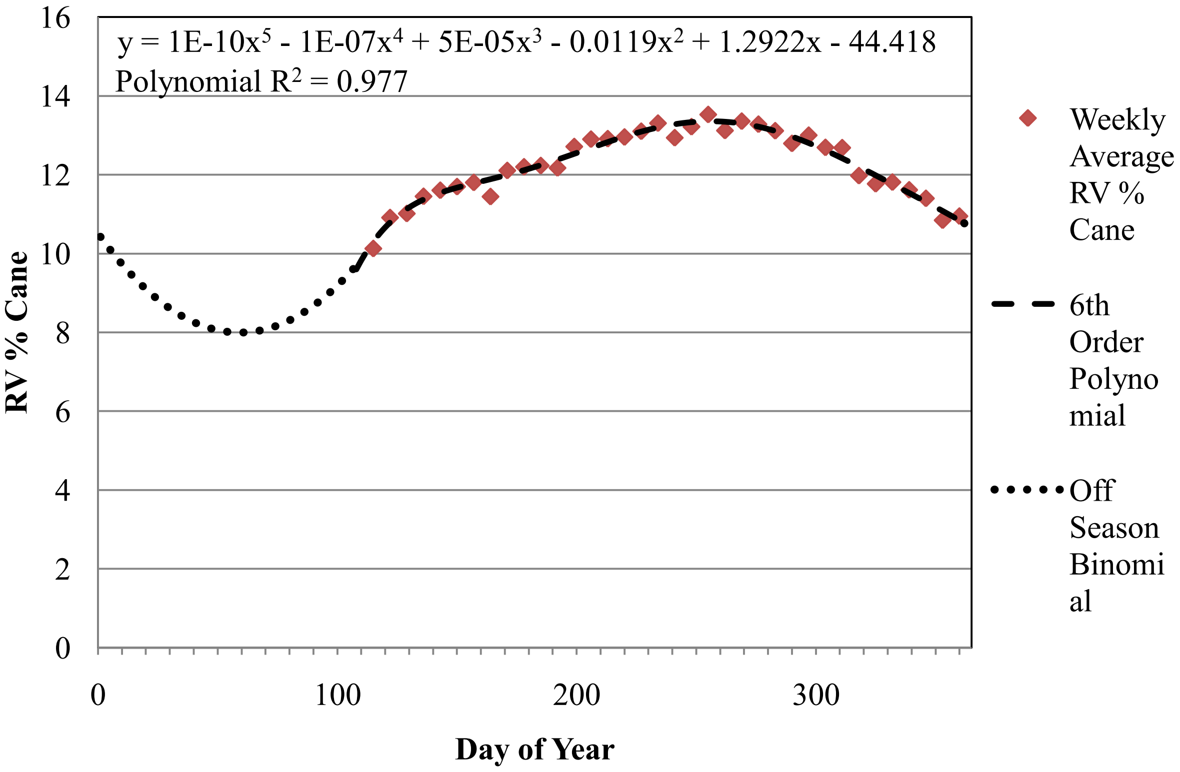

Figure 3.8 Variation of RV% cane at Umfolozi Sugar Mill

3.8 Sucrose Deterioration in the Stockpile

The sugar supply chain is affected at all times by the deterioration of sucrose after harvesting. It has been found that in order to reduce losses in revenue, the harvest to crush delay (HTCD) should be reduced to a minimum (Lyne and Meyer, 2005). The implementation of the stockpile will add an additional 24-hour delay to the HTCD. A calculation of the sucrose loss that occurs in the stockpile was required to ensure that the model does not over-estimate the positive economic effect associated with a stockpile. Lionnet (1986) demonstrated that mathematical equations can be used to estimate sucrose loss, the rate of which is dependent on temperature. Using this method and daily temperature data at the mill a daily percentage deterioration during the milling season was calculated.

Data from the ULOA Weather Station was used to calculate the average daily temperature in degrees Celsius for Umfolozi. The average temperature for each day of the year was plotted in Figure 3.9. This data was used as the temperature input in Lionnet"s (1986) deterioration calculation. It should be noted that the temperature used was from a Stephenson Screen temperature gauge which records the ambient temperature in shade. The actual temperatures experience by the stockpile in direct sunlight may be far greater. In addition, the deterioration of sucrose is an exothermic reaction and will thus increase the temperature of the sugarcane (Lionnet, 1986). The decision to use the Stephenson Screen temperature in calculating sucrose loss was conservative and actual values for sucrose loss may be far greater.

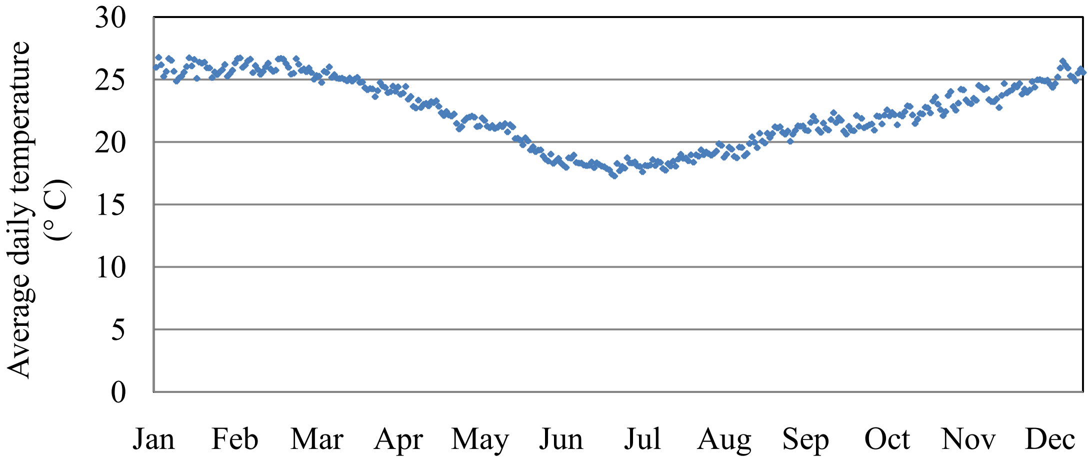

Figure 3.9 Average daily temperature at Umfolozi

The deterioration of sucrose may be assumed to be a chemical process with reactants and products occurring at a certain rate (Lionnet, 1986). It is therefore possible to apply the integrated first-order rate law (Equation 3.1) to estimate deterioration (Lionnet, 1986; Zumdahl and Zumdahl, 2000)

$$A_t = A_0 . e^{-k_1 . t} \qquad (3.1\ )$$

Where: A_t = concentration of sucrose at time t

A_0 = concentration of sucrose at time zero

k_1 = first order rate constant

t = time in hours

Assuming that temperature had a significant effect on the rate of deterioration and based on data from experimentation and data sets from different countries Lionnet (1986) obtained an estimate for the first order rate constant. Equation 3.2 was Lionnet‟s (1986) result of assessing the effect of temperature using the Arrhenius equation.

$$\log_e k_1 = -\frac{9498}{T} + 24.1 \qquad (3.2\ )$$

Where: T = Average temperature experience by the sugarcane (K)

Rearranging Equation 3.2 gives:

$$k_1 = e^{\left(-\frac{9498}{T}+24.1\right)} \tag{3.3}$$

Substituting Equation 3.3 into Equation 3.1 gives:

$$A_t = A_0 . e^{-\left[e^{\left(-\frac{9498}{T}+24.1\right)}\right].t} \tag{3.4}$$

Assuming that sugarcane entering the stockpile had a sucrose concentration of A_0 and the concentration of sucrose leaving the stockpile after 24 hours was by A_1 then the percentage of sucrose lost was calculated as in Equation 3.5.

$$SL\,\% = 100\frac{A_0 - A_t}{A_0} \tag{3.5}$$

Where: SL = sucrose loss (%)

Substituting Equation 3.4 into Equation 3.5 provides an estimate for the percent deterioration (Equation 3.6).

$$SL\,\% = 100\frac{A_0 - \left\{A_0 . e^{-\left[e^{\left(-\frac{9498}{T}+24.1\right)}\right].t}\right\}}{A_0} \tag{3.6}$$

As an example if the average temperature on 1 May was 22°C (T = 273 + 22 = 295°K), sugarcane remained in the stockpile for 24 hours (t = 24 hours) and the amount of sucrose present in the sugarcane before entering the stockpile was 13 % of the total mass (A_0 = 13 %). Then the percentage of sucrose lost due to deterioration can be calculated as follows:

$$SL\,\% = 100\frac{(13\%) - \left\{(13\%) . e^{-\left[e^{\left(-\frac{9498}{295}+24.1\right)}\right].24}\right\}}{(13\%)}$$

$$SL\,\% = 0.73\,\%$$

Therefore, 0.73 % of the sucrose present in the sugarcane is lost due to deterioration, i.e. the percentage of sucrose in the sugarcane after remaining in the stockpile was:

$$Sucrose\ \%\ after\ stockpile = 13\% - \left(\frac{0.73}{100} \times 13\%\right) \tag{3.7}$$
$$Sucrose\ \%\ after\ stockpile = 13\% - 0.0936\%$$
$$Sucrose\ \%\ after\ stockpile = 12.905\ \%$$

The above method was applied to all sugarcane which passed through the stockpile. The percentage of sucrose lost varied according to the average temperature of each day throughout the milling season.

3.9 Capital Investment and Budgeting

The construction of additional tram trucks are the only capital expenditure required to implement a stockpile at Umfolozi. A stockpile of 3696 tons would require 711 tram trucks (5.2 ton loading capacity). The mill is currently operating with a surplus of 100 trucks (McGrath, 2010). The mill area would therefore have to invest in an additional 611 trucks. The current cost of a new tram truck is approximately R 18 000. The stockpile would therefore require an initial investment of R 10 998 000. The rail system does not require any changes to accommodate the stockpile (Figure 3.3).

Capital budgeting is a procedure for evaluating the effects of management‟s investment choices on a business‟s profitability, risk, and liquidity (Barry *et al.*, 2000). It helps managers to identify potential investment options and provides a means of assessment of the investment. A capital budget of the savings generated by each scenario was carried out. The capital budget calculates the present value of income generated in the future. The capital budgeting method accommodates the depreciation of capital over three years at a rate of 50%, 30% and 20%, respectively. The depreciation of capital was tax deductable. The present value (PV) of the net cash flow was calculated for each year in the future. The PV Was then subtracted from the total capital expenditure in order to determine the number of years it will take for the investment to break even. The inputs into the capital budget are given in Table 3.5.

Table 3.5 Input parameters to the capital budget

Variable	Value
Initial Investment	R 10 998 000
Depreciation of Capital	
Year 1	50%
Year 2	30%
Year 3	20%
Discount Rate	5%
Risk	2%
Tax on revenue	40%

3.10 Simulations

Monte Carlo simulations were carried out to generate results for LOMZI. Monte Carlo simulations are best suited for simulations where there is uncertainty and a wide range of inputs in the model (Tijms, 2003). There are a number of methods that can be followed when running Monte Carlo simulations (Tijms, 2003). In most situations they follow the following four steps.

1. Define input domain,
2. Generate inputs randomly from the domain,
3. Run the model using the inputs, and
4. Aggregate the results of the model into one result.

In the case of LOMZI, the domain of random inputs was the possible rainfall that could occur at Umfolozi. Random generators in the model generated typical seasons of rainfall. For example, some years could be considered drought seasons while others would be above average rainfall. This information was run through the model and a group of results was obtained for each setting of independent inputs. For each simulation a control was also attained by simultaneously running the model with no stockpile. This ensured that each season was compared to a reference year on year.

Three different scenarios were assessed, as described below. The three scenarios were simulated over 1000 stochastic seasons.

Scenario 1: Assume zero percent deterioration in the stockpile, and maintain the stockpile throughout the season.

Scenario 2: Assume zero percent deterioration in the stockpile, and maintain a stockpile only during the summer.

Scenario 3: Assume different degrees of deterioration (from 0 to 1% RV per day) in the stockpile and maintain the stockpile throughout the season.

4. RESULTS AND DISCUSSION

A series of simulations were carried out while varying the inputs to the LOMZI Model. Each run of the model consisted of 1000 stochastic seasons. The output was aggregated into a set of graphs that indicate the opportunities around the creation of a stockpile.

4.1 Stockpile Simulations

A sensitivity analysis of the results was carried in line with standard procedures (Saltelli *et al.*, 2004). Figure 4.1 shows how the average quantity of cane in the stockpile varies through the milling season and the average number of no-cane stops each month. During the winter months, May to August, the average amount of cane present in the stockpile is approximately 2 500 tons, which when including cane from the dry areas is equivalent to 18.6 hours of stock and relatively close to the 24 hour buffer that is provided. The cane quantity then drops rapidly to 1 750 tons by mid October or 15.1 hours of stock. This can be attributed to the change in rainfall probabilities as depicted in Figure 3.5. The average number of no-cane stops with a stockpile present changes from 1.5 days to 2.2 days between September and October. During spring there is an increase in the rainfall probability, with more frequent and prolonged rainfall events decreasing the average daily stockpile of cane. In order to achieve greater stockpile effectiveness it may be worth considering increasing the capacity of the stockpile to 48 hours during the prolonged rainfall event periods.

Considering the lower utilisation of the stockpile during winter it may be worth switching the stockpile off. However, it has been shown that the stockpile is more effective in mitigating one day rainfall events, which are more frequent in winter as shown in the consecutive day rainfall probability analysis in Figure 3.5.

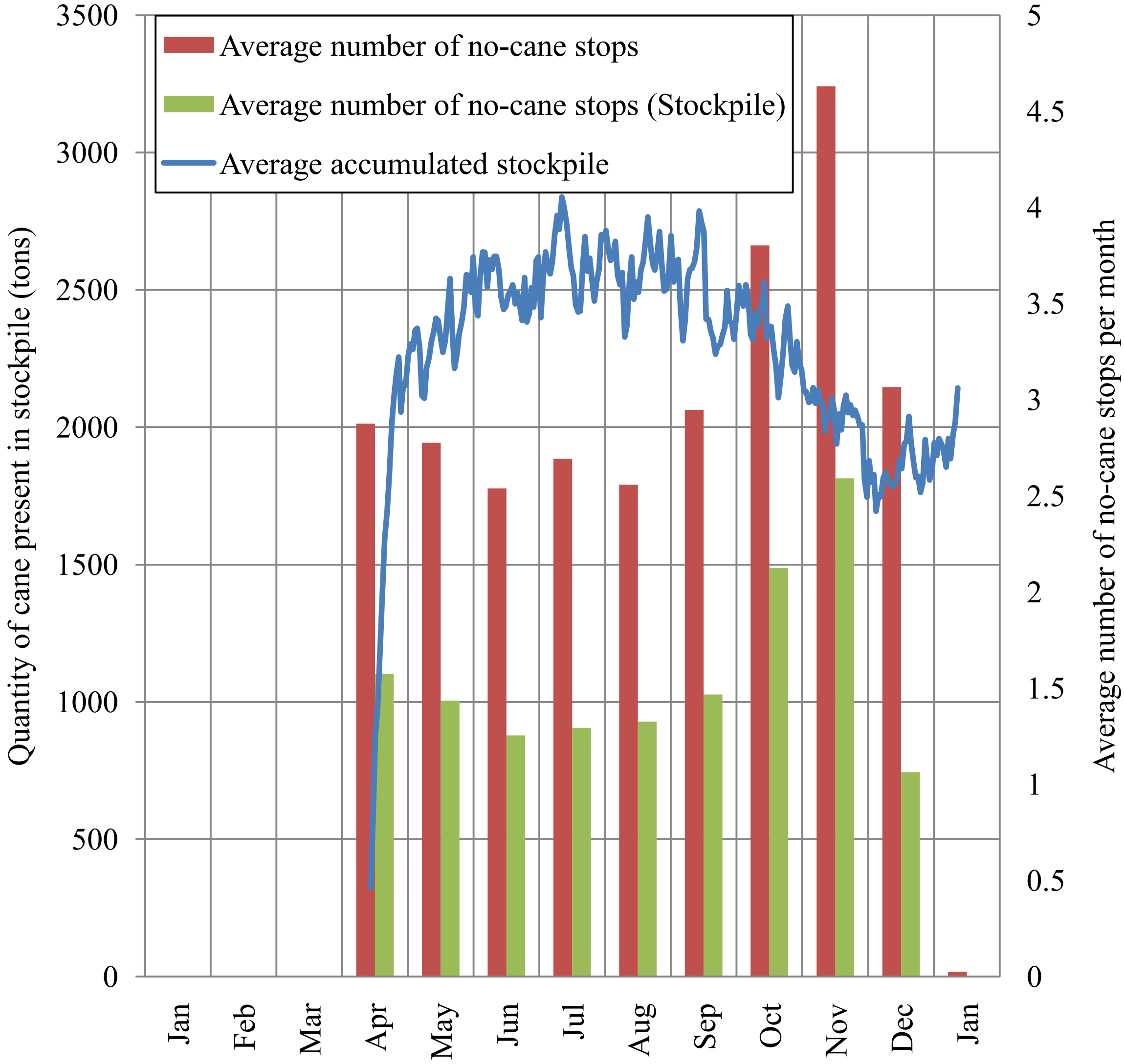

Figure 4.1 Average quantity of cane present in the stockpile (tons) throughout the season (cane deterioration excluded)

Figure 4.2 illustrates the extent to which the stockpile reduced the length of the milling season (LOMS). With an increase in the number of wet field days, *i.e.* days that harvesting is not possible on the Umfolozi Flats, there is an increase in the benefit of the stockpile. This can be seen in the widening of the linear lines towards the right of the graph. At the minimum number of wet field days the stockpile decreases the LOMS by six days. At the maximum number of wet field days there is a reduction in the LOMS by 12 days. There will be a rise in mill area profits as a result of a larger proportion of cane crushed at a peak RV due to the reduced LOMS. A simple rule of thumb could be derived from these results, which proposed that a 24 hour stockpile will reduced the LOMS by one day for every 2.7 wet days in the season.

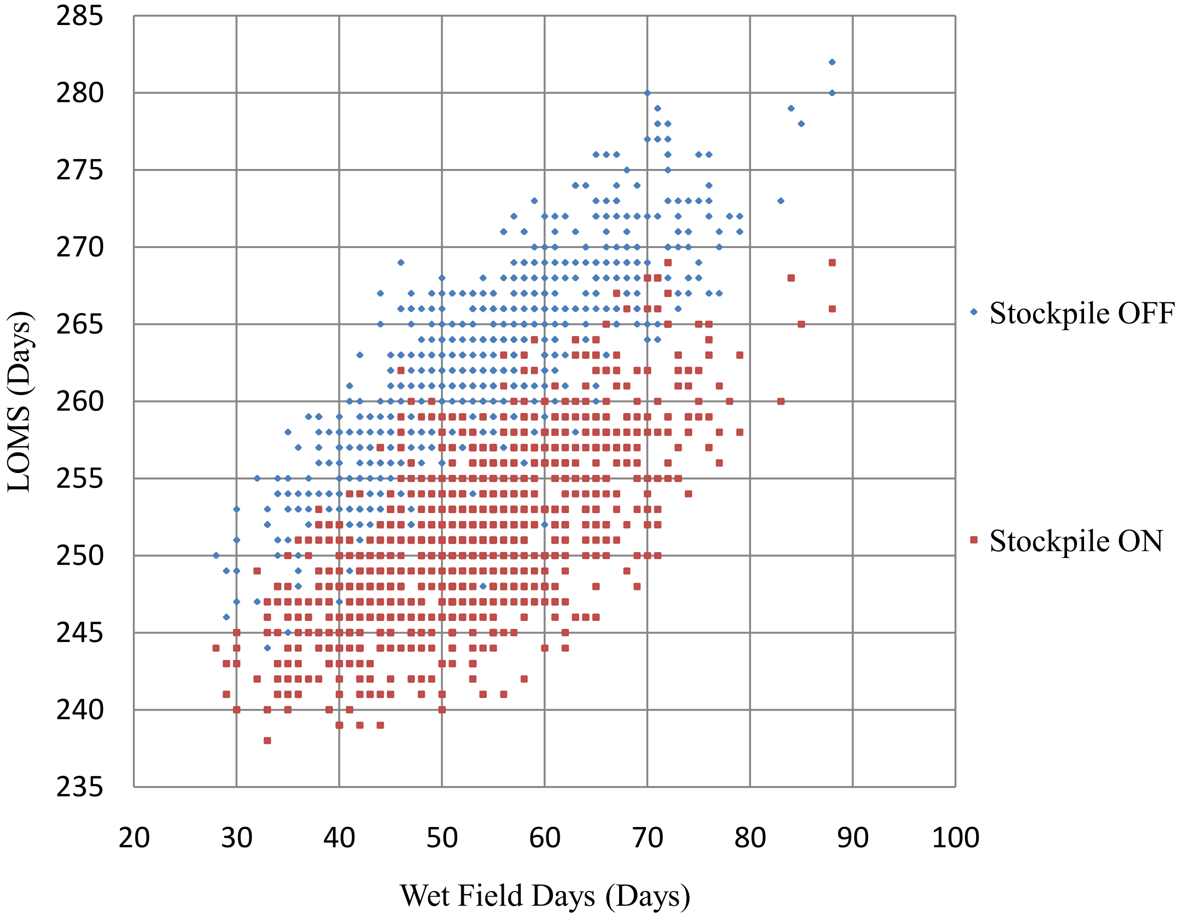

Figure 4.2 The simulated trend between LOMS, the number of wet field days and the implementation of a stockpile at Umfolozi Mill (cane deterioration excluded)

The reduction in LOMS was also reflected in the change in the total length of no-cane stops. The length of no-cane stops both without a stockpile and with a stockpile present have been plotted in Figure 4.3. At an average of 52 wet field days, the stockpile reduced the total length of no-cane stop hours by 52%.

The savings that will occur as a result of implementing the stockpile comprise two main components: (a) savings as a result of reducing the number of mill stops, and (b) savings as a result of crushing more cane during the peak RV period. Savings are classified as purely the difference between the profits generated without a stockpile present and with a stockpile present while assuming all other costs were constant. This amounted to a total of R 2 560 000. Savings achieved by reducing the number of mill stops contributed 22% towards the total savings amount, while RV savings contributed 78%.

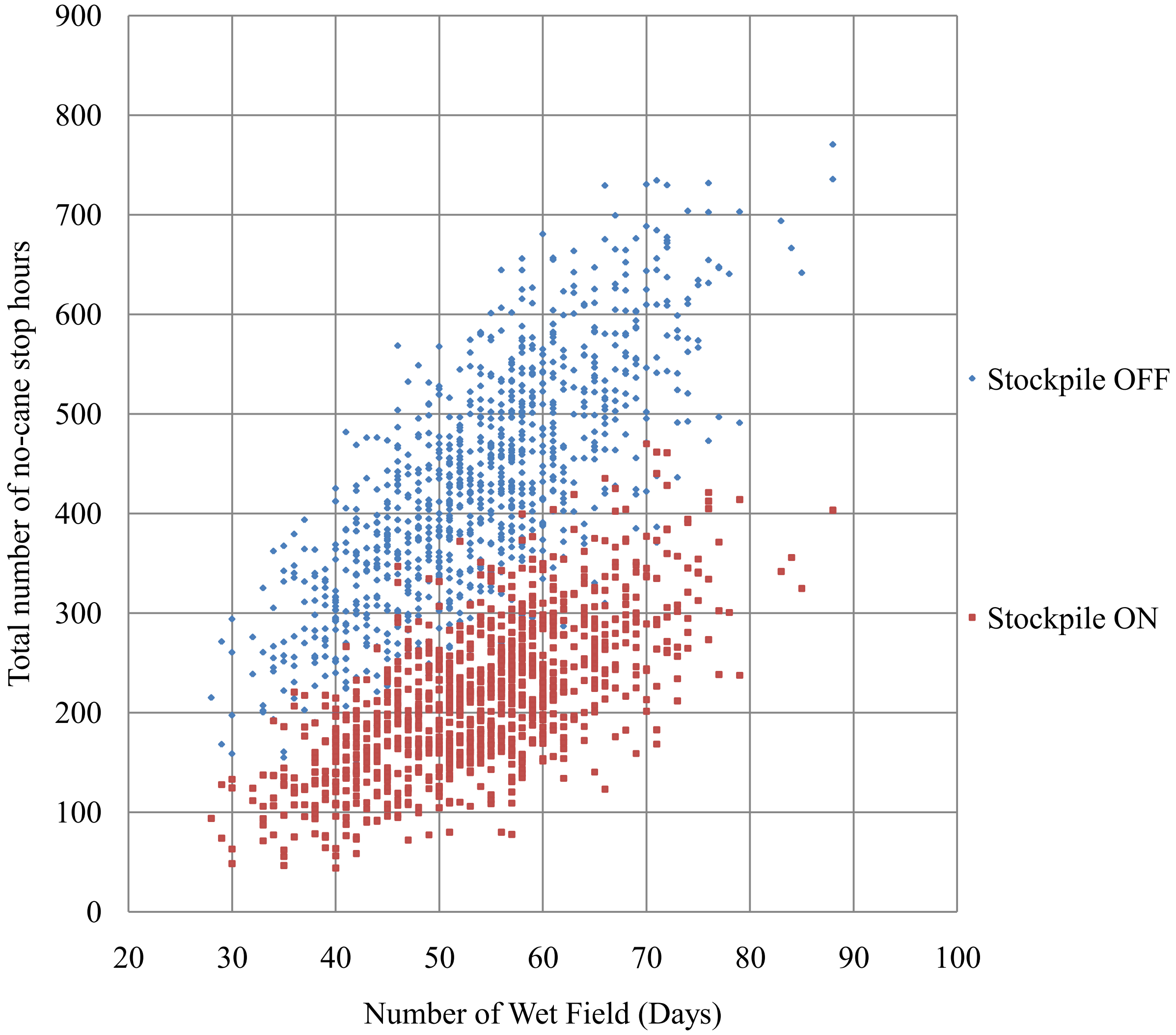

Figure 4.3 The simulated trend between total number of no-cane stop hours, wet field days and the implementation of a stockpile at Umfolozi Mill (cane deterioration excluded)

The savings incurred by reducing the length of the milling season are represented in Figure 4.4. The stockpile and non-stockpile scenarios as well as the difference between them is plotted and second order polynomials were fitted to the data, thus allowing earnings comparisons on a season to season basis. The difference in earnings increases non-linearly with an increase in the number of wet field days.

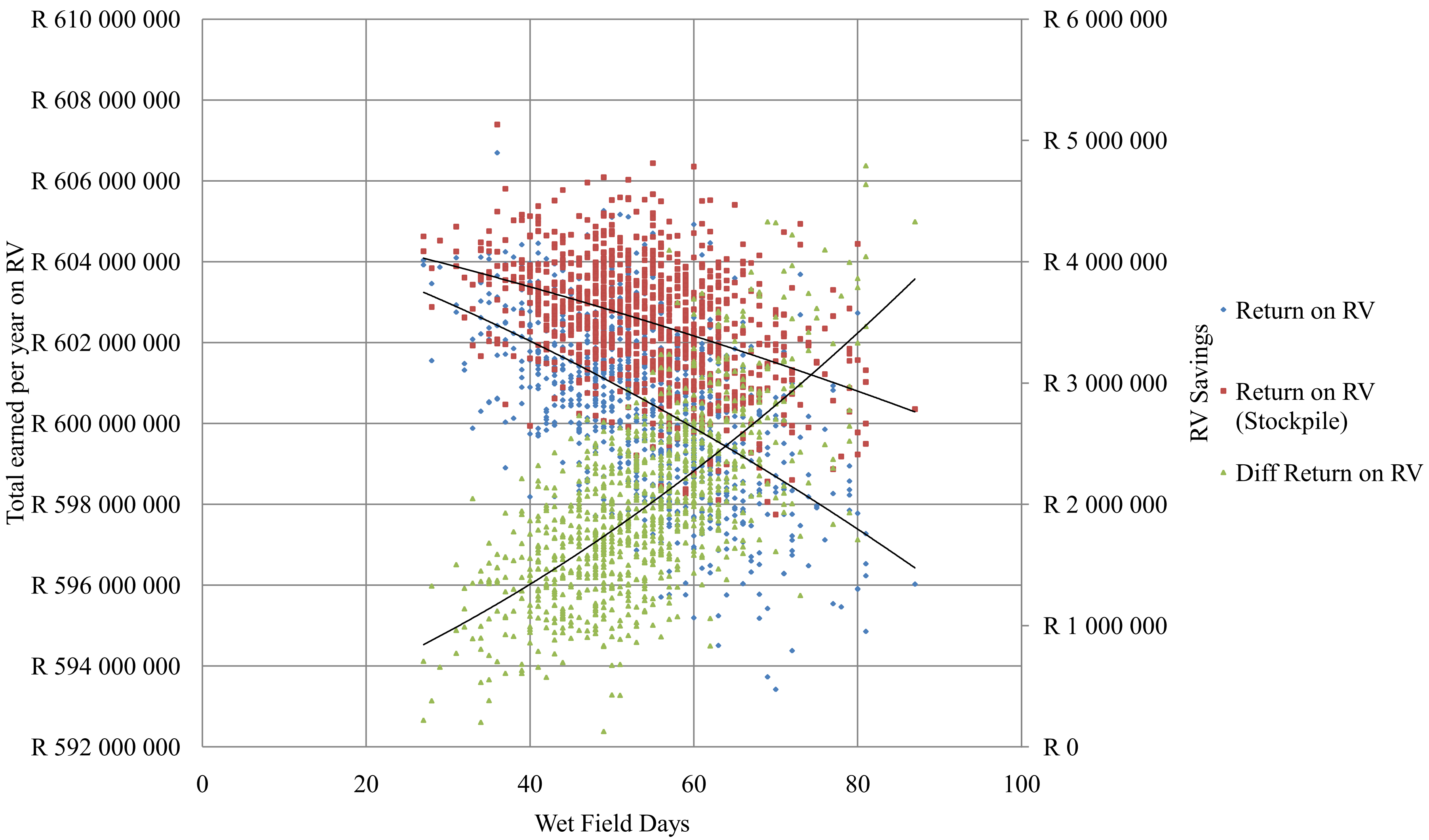

Figure 4.4 The potential savings materialised when implementing a stockpile against the number of wet field days (cane deterioration excluded)

Figure 4.5 represents the histogram of total savings data of 1000 simulated seasons. The mean was chosen to represent the most likely outcome from the model. At mean of R 2 560 000 the capital investment of the trams, R 10 998 000 (Section 3.9), would be expected to break even in approximately 5 seasons. The capital budget for this scenario is depicted in Table 4.1.

If the savings were to increase by 20%, there was a 20% decrease in the number of seasons that it would take for the investment to break even. However, if there was a 20% decrease in savings the number of seasons to break even increases by 40%. The capital budget therefore becomes more sensitive as the amount of savings decreases. This emphasises the vulnerability of the stockpiles‟ ability to repay the capital expenditure and depicts a decision with a relatively high risk attached to it.

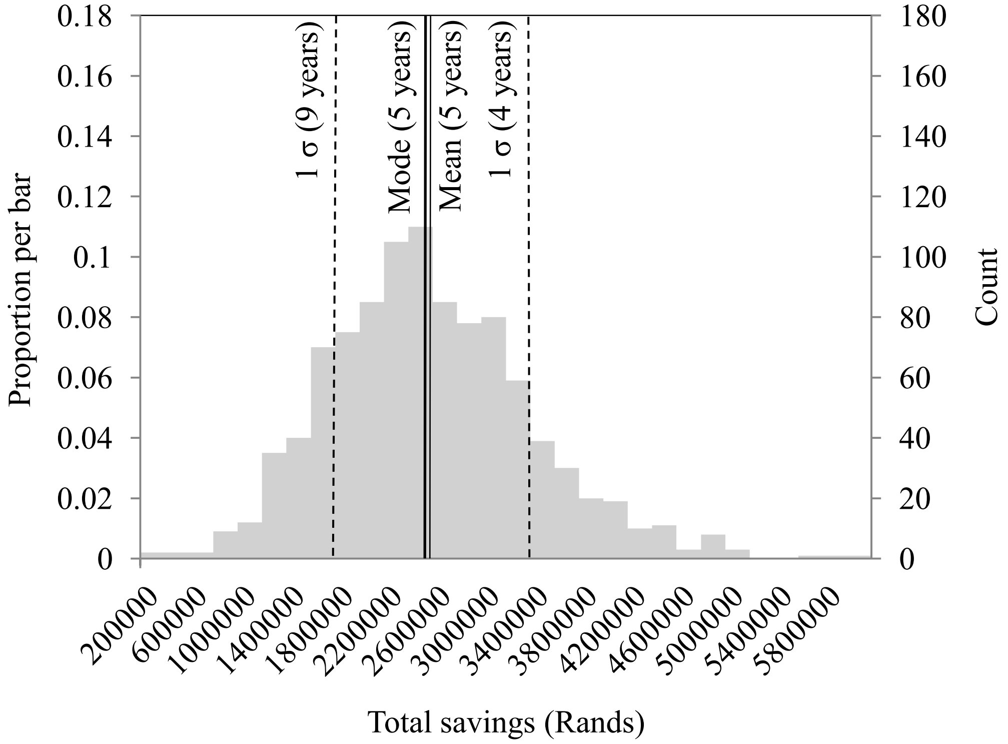

Figure 4.5 A histogram of 1000 seasons of total saving due to stockpiling at Umfolozi (cane deterioration excluded)

Table 4.1 Capital budget for a saving of R 2 560 000, definitions of the terms used are provided in Appendix A (cane deterioration excluded)

Step	**Year**	**0**	**1**	**2**	**3**	**4**	**5**	**6**
1	Investment (-ve)	-10998000						
2	Depreciation of Capital		-5499000	-3299400	-2199600			
3	Cost Saving per Year		2560000	2560000	2560000	2560000	2560000	2560000
4	Total Annual Cost Saving (Real)	-	2560000	2560000	2560000	2560000	2560000	2560000
5	Change on Taxable Income	-	-2939000	-739400	360400	2560000	2560000	2560000
6	Change in Tax (40%)	-	-1175600	-295760	144160	1024000	1024000	1024000
7	Change in Net Cash Flow	-10998000	3735600	2855760	2415840	1536000	1536000	1536000
8	PV of Δ Net Cash Flows (i = 7%)	-10998000	3491215	2494331	1972045	1171807	1095147	1023502
9	Accumulative Net Income	-10998000	-7506785	-5012454	-3040409	-1868602	-773455	250047
10	Percentage of Investment Returned	0%	32%	54%	72%	83%	93%	102%

Figure 4.6 demonstrates the sensitivity of the lower values of total savings in relation to repaying the capital investment. Below R 1 000 000 the number of seasons to break even increases exponentially, therefore, an investment in the tram system will not make financial sense. The model estimates that in 1000 seasons, 1.4% of the seasons would generate a saving of less than R 1 000 000.

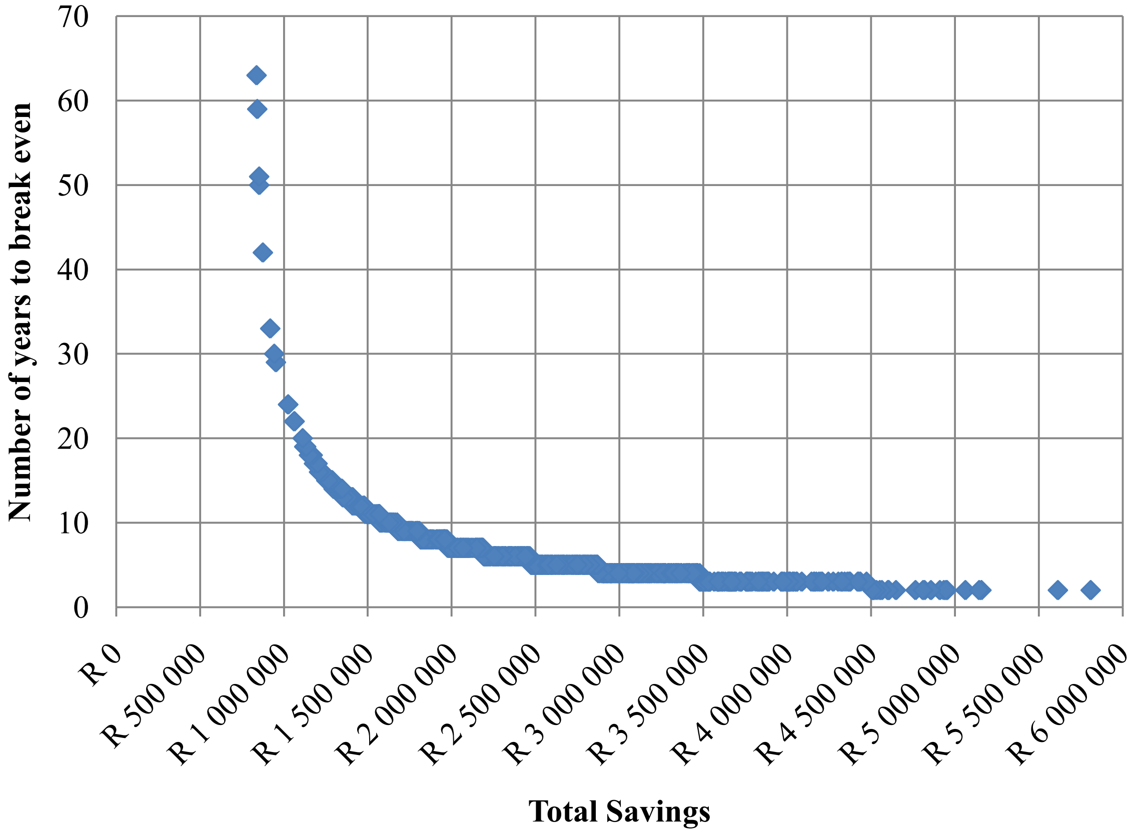

Figure 4.6 Seasons to break even with change in total savings (cane deterioration excluded)

4.2 Cane Deterioration

The simulations in Section 4.1 were carried out with the cane deterioration in the stockpile set at zero. This is unrealistic for cane that is stockpiled outside the mill for 24-hours. When this adjustment was added to the model, there was no advantage achieved as a result of money saved from the reduction in mill stops and a peak RV percent cane crush. The difference between the savings generated by the stockpile and the cost of deterioration demonstrates the detrimental effect that cane deterioration has on the earnings of a sugar supply chain. With deterioration set to zero the mean total saving generated by the stockpile was R 2 560 000, however, when deterioration was set to the level determined using Lionnet‟s (1986) mathematical approach and daily temperature data, the mill area lost an estimated total of R 1 160 000 per annum.

When considering the above values, it was apparent that the implementation of a 24-hour stockpile adds to the cost of running the mill. Based on Lionnet‟s (1986) findings, Figure 4.7 was generated to demonstrate the typical effect of deterioration on the total savings generated by the stockpile. The blue line represents the percentage deterioration of the original RV % and the green line represents the total savings generated by the stockpile relative to temperature. For example, at 17 °C there was 0.4 % deterioration of the original RV %. If the original RV % present in the sugarcane was 13 % (A_0) then the RV % remaining (A_1) in the sugarcane after 24 hours at 17 °C would be calculated as shown in Equation 4.1.

$$A_1 = A_0 - \left(\frac{\%\ deterioration}{100} \times A_0\right) \qquad (4.1\ \ )$$

$$A_1 = 13\ \% - \left(\frac{0.4\ \%}{100} \times 13\ \%\right)$$

$$A_1 = 12.95\ \%$$

If the temperature of the stockpile was maintained at 17 °C throughout the milling season the stockpile would breakeven and would not result in any savings to the mill area. This is a highly unlikely scenario as the temperature of the stockpile most certainly exceeds 17 °C in direct sunlight and with the added effect of respiring sugarcane. It was apparent that at relatively low ambient temperatures deterioration severely affected the total amount of savings. These results point to an unviable scenario.

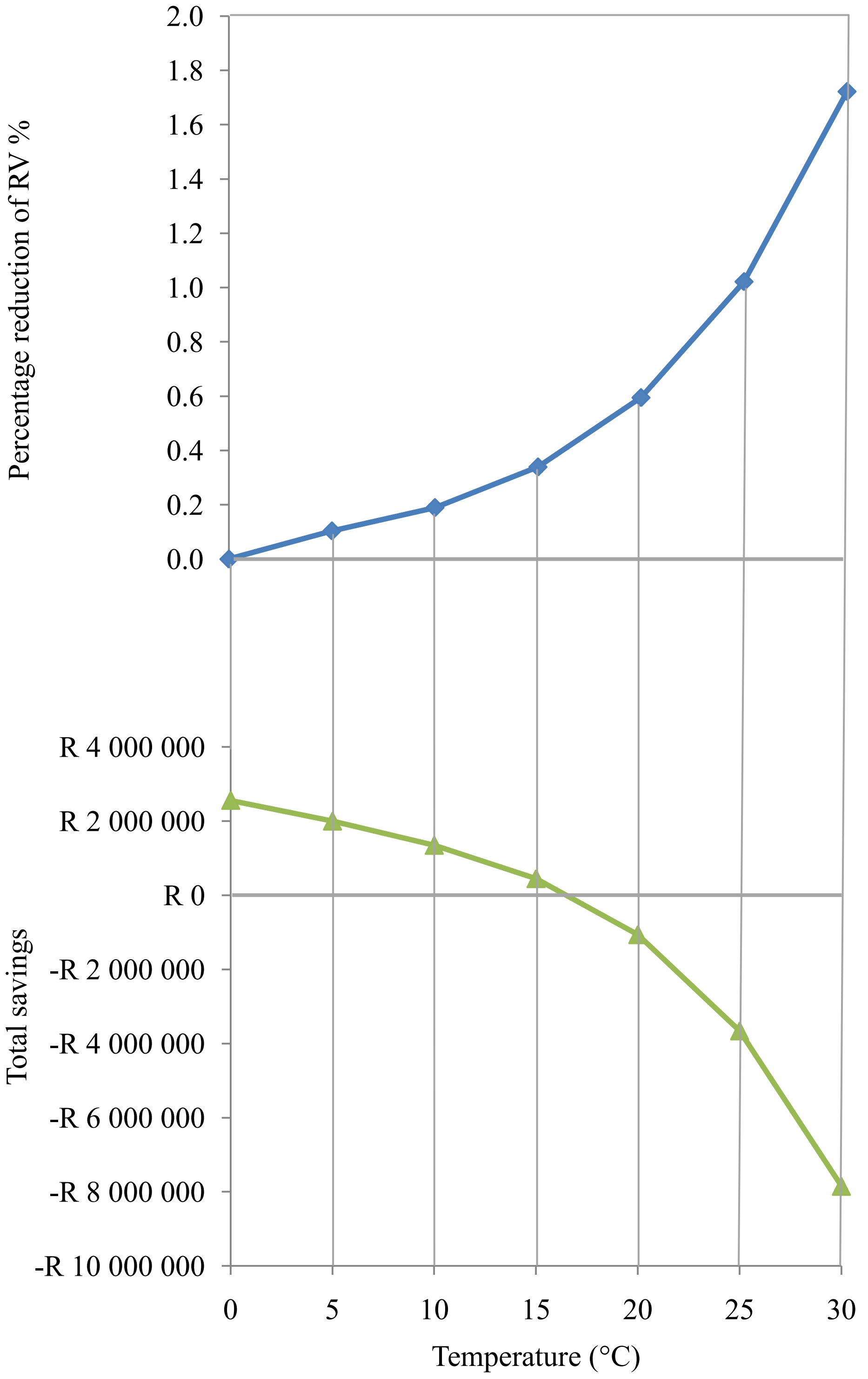

Figure 4.7 Total savings sensitivity to the percentage reduction of RV % at varying temperatures

4.3 Discussion

The LOMZI model inadvertently highlights the costs of interactions between the mill and the fields. The costs are broken down into three sections: (a) the effect of LOMS on the earnings of the mill area, (b) the cost of deterioration, and (c) the cost of mechanical mill stops.

Creating a stockpile during the entire season decreased the LOMS by an average of 9 days. The decreased LOMS created a savings of R 1 999 000, when the cane deterioration inside the stockpile was assumed negligible. The slight change in the LOMS and the subsequent effect on earnings is worth noting and must be carefully considered when new technologies or management scenarios are considered.

When a more realistic degree of deterioration was factored into the model, the losses that were incurred were dramatic. The stockpile no longer saved money, but actually cost the mill approximately R 1.2 million per annum. Deterioration deems the stockpile unviable, but also highlights the importance (or possible severity) of any management decision that would lengthen the harvest to crush delay. This indirect result should caution stakeholders.

5. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

5.1 Conclusions

Sugar milling is extremely sensitive to cane supply consistency and cane quality as highlighted in the literature review. Rainfall disrupts infield harvesting and increases the amount of soil that enters a mill. The disruption to harvesting is often severe enough to cause a mill no-cane stop. An unexpected no-cane stop decreases sugar production efficiency. Processes that are particularly affected are diffusion, clarification and crystallisation. The degree of deterioration is also increased due to the longer residence time of sucrose in the various stages of sugar production. The combined effect is an increase in the cost of sugar production. In order to reduce the number of no-cane stops a modelling framework LOMZI was developed.

This research has created a mechanistic tool to drive decision making at the Umfolozi Sugar Mill. It has documented the development and testing of a stochastic simulation model, LOMZI. The model has achieved its purpose by providing significant and useful feedback to the Umfolozi Mill. There have, however, been additional benefits realised during the development of LOMZI.

The significance of the modelling framework is that LOMZI has, to the author‟s knowledge, been the first modelling framework to stochastically include the effect of rainfall patterns on the length of milling season (LOMS). The incorporation of rainfall patterns sets LOMZI apart from other models in that a more comprehensive simulation of possible seasons is now possible. It has potentially created a new modelling framework where more emphasis is placed on environmental factors and risks. The incorporation of environmental factors such as the change in rainfall patterns may have a significant effect on the current perception of the optimum LOMS as well as how the mill operates during the season.

In addition to questioning the LOMS, this study has once again emphasised the crippling effect of cane deterioration. Inducing a further 24 hour delay as a result of a stockpile in combination with high temperatures brings about a significant increase in the amount of deterioration. Above an ambient temperature of 17 °C stockpiling harvested cane outside the mill for 24 hours no longer brought about any financial gain. Therefore, it was concluded that creating a stockpile of cane outside the mill should be approached with extreme caution because of the non-linear sensitivity to temperature in the final outcome.

This study highlights the importance of cane deterioration, LOMS, risk management and how it relates to the integrated supply chain. It demonstrates how, on a large scale, a cane supply dynamics model can be developed and successfully tested to reach a conclusion. In developing LOMZI a framework has been created that could have a similar application to other milling areas.

5.2 Recommendations for Further Research

LOMZI was successfully implemented at Umfolozi, however, in order for the LOMZI framework to become more versatile some future adjustments may be required.

- Deterioration in the cane quality has been quantified using Lionnet"s (1986) method of assessing the effect of temperature by applying the Arrhenius equation. It can be assumed that there is a high variability in the temperature of harvested cane from burn to crush. During and after burning the temperature will be extremely high and therefore may increase the rate of deterioration. After cooling the rate of deterioration may decrease to an acceptable level. If this is the case, then an additional 24 hours in the stockpile may be less severe relative to the deterioration soon after burning. Further research is needed at Umfolozi to monitor how the temperature of harvested cane varies through the supply chain.

- LOMZI did not account for a variable mill crush rate. If the mill is running behind schedule the crush rate can be increased to maintain the predicted LOMS and visa versa. By including the variable crush rate in the model a more accurate prediction of the LOMS may be achieved.

- The structure that LOMZI developed was rigid and applied only to the Umfolozi Mill. Some aspects of LOMZI such as the mill mechanical breakdown generator will be useful in future models and in other regions. A suggestion, therefore, is that future models in similar fields become more object orientated. This will allow for easier adaptation and more flexibility.

- Additional rainfall stations could be added to the rainfall data using triangulation. This would result in a more accurate simulation of the rainfall patterns. A more comprehensive perspective of how rainfall affects the supply area will help the model deal with rainfall variability. Hence, it would be possible to model only parts of the cane supply being affected by rainfall.

- LOMZI highlights the damaging result of prolonged rainfall events in early October. Further research in the effect of these rainfall events may show that it might make more economic sense for the mill to shut down for a long maintenance during this period and reopen once the weather has stabilised into summer.

- Upon further analysis it was apparent that the current frequency of mechanical breakdowns experienced at Umfolozi Mill seems more detrimental to the system than no-cane stops. A model or similar framework could be created to estimate the financial gains of increasing the maintenance, thus preventing frequent breakdowns. Once again, the extended LOMS and decline in RV can be anticipated as a significant loss.

- The stockpile in LOMZI was maintained at all times throughout the season. With effective weather forecasting the stockpile need only be created with the approach of wet weather. This would decrease the impact that the deterioration would have in LOMZI, but relies on forecast accuracy and risk management.

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7. APPENDICES

Appendix A. Definition of terms used in the capital budget (Barry *et al.*, 2000)

Term	Definition
Investment	The initial equity the investor commits to the project.
Depreciation of Capital	An accounting procedure by which the purchase cost of a depreciable asset, in this case the tram trucks, in prorated over its projected economic life.
Total Annual Cost Saving (Real)	Yearly savings as a result of the implementation of the capital investment.
Change on Taxable Income	Total savings generated by the investment less depreciation.
Change in Tax (40%)	Tax rate on taxable income.
Change in Net Cash Flow	Taxable income less tax.
PV of Δ Net Cash Flows (i = 7%)	Accounts for the timing and magnitude of the projected cash flows in the future.
Accumulative Net Income	Total income as a result of the investment summed year on year.
Percentage of Investment Returned	Accumulated net income divided by initial investment

Appendix B. Inputs to model

Variable	Value	
Number of Simulations	1000	
Slowest Daily Crush	2 000	tons
Slowest Crush Cost	R 115 000	per day
Season Length Days	254	days
Average Seasonal Crush	1 100 000	tons
Regeneration of Stockpile	0.1	
Mill Season Start	08-Apr	
Rands Per Ton RV	R 4 500	per ton RV
Rands Per Ton Coal	R 710	per ton coal
Cost per ton Liquidation Losses	R 4 400	per ton sucrose
Capacity of Stockpile	3 711	tons
Possibility of breakdown during any day	64%	
Factor for Deterioration	1	
Delay From Harvest	24	hr
Percent Deterioration of Stockpile	0.03250	%
Stockpile Switch	08 Apr	on
	31 Dec	off
	01 Jan	on
	31 Jan	off

Average Mill Close Date	24-Dec	
Average Mill Close Date (Stockpile)	16-Dec	
Percentage Spilt between Tram and Road		
Tram	70%	
Road	30%	
Mill		
Weely Crush	37 000	tons
Daily Crush	5 286	tons
Tram		
Last 5 year average weekly delivery	25 978	tons
Last 5 year average daily delivery	3 711	tons
Road		
Last 5 year average weekly delivery	11 022	tons
Last 5 year average daily delivery	1 575	tons

Appendix C. Example of a line of equations from the model

Variable	Equation
DOY	1
Date	2010/01/01
5 <= X < 10 mm	=[UmfoloziModel.xlsm]RainfallGenerator!E9
10 <= X < 30 mm	=[UmfoloziModel.xlsm]RainfallGenerator!E10
X >=30 mm	=[UmfoloziModel.xlsm]RainfallGenerator!E11
Fields Wet	0
Fields Wet Flag	=IF(B6,1,0)
Potential Daily Tram Delivery	=IF(B2>=[UmfoloziModel.xlsm]Input!$B$9,[UmfoloziModel.xlsm]Input!$B$28,0)
Rain effected Tram Delivery	=IF(B6,0,B8)
Stockpile 10% per day	=MAX(IF([UmfoloziModel.xlsm]Input!$B$17<B2,IF(B2<[UmfoloziModel.xlsm]Input!$B$18,[UmfoloziModel.xlsm]Input!$B$8*B9,0),0),IF([UmfoloziModel.xlsm]Input!$B$19<B2,IF(B2<[UmfoloziModel.xlsm]Input!$B$20,[UmfoloziModel.xlsm]Input!$B$8*B9,0),0))
Accumulated Cane Stockpile	=IF(B10>0,IF(A11<[UmfoloziModel.xlsm]Input!$B$13,SUM(B10,A11),A11),0)
Amount of Stockpile Cane Crushed	=IF(B6,A11,0)
Cane from dry area	=IF(B2>=[UmfoloziModel.xlsm]Input!$B$9,[UmfoloziModel.xlsm]Input!$B$31,0)
breakdown	=IF(RAND()<[UmfoloziModel.xlsm]Input!$B$21,1,0)
X	=IF(B14=1,RAND(),"")
p	0.868918647354255
q	4.79062183921832
min	1
max	24
Hour Breakdown Simulator	=IF(B15<>"",BETAINV(B15,B16,B17,B18,B19),0)
Breakdown Stop Flag	=IF(B20>0,1,0)
Breakdown Stop Flag (Stockpile)	=IF(B20>0,1,0)
Inseason Breakdown Stop Flag	=IF(B41>0,B21,0)

Inseason Breakdown Stop Flag (Stockpile)	=IF(B42>0,B22,0)
Breakdown Hours	=IF(B21>0,B20,0)
Breakdown Hours (Stockpile)	=IF(B22>0,B20,0)
Inseason Breakdown Hours	=IF(B41>0,B25,0)
Inseason Breakdown Hours (Stockpile)	=IF(B42>0,B26,0)
	=B9+B13
Mechanical Breakdown Effected Maximum Crush Rate	=[UmfoloziModel.xlsm]Input!$B$25-([UmfoloziModel.xlsm]Input!$B$25*(B25/24))
Min Column Y and Z	=MIN(B29:B30)
	=[UmfoloziModel.xlsm]Input!$B$7
Cane Remaining	=IF(A32<A29,IF(B32>0,A32-A32,0),B32)
In Season Daily Crush	0
,	=SUM(B9,B12,B13)
Mechanical Breakdown Effected Maximum Crush Rate (Stockpile)	=[UmfoloziModel.xlsm]Input!$B$25-([UmfoloziModel.xlsm]Input!$B$25*(B26/24))
Min Column AE and AF	=MIN(B35:B36)
	=[UmfoloziModel.xlsm]Input!$B$7
Cane Remaining (Stockpile)	1100000
In Season Daily Crush (Stockpile)	0
Mill open/closed	=IF(B34>0,1,0)
Mill open/closed (Stockpile)	=IF(B40>0,1,0)
Reduced minimum crush rate as a result of mechanical mill stop	=[UmfoloziModel.xlsm]Input!$B$4-([UmfoloziModel.xlsm]Input!$B$4*(B25/24))
Daily Total Crush showing mill no cane stops	=IF(B41>0,IF(B34>=B43,B34,IF(C44<>0,"mill stop!!!",B34)),0)
Reduced minimum crush rate as a result of mechanical mill stop (Stockpile)	=[UmfoloziModel.xlsm]Input!$B$4-([UmfoloziModel.xlsm]Input!$B$4*(B26/24))

Daily Total Crush showing mill no cane stops (Stockpile)	=IF(B42>0,IF(B40>=B45,B40,IF(C46<>0,"mill stop!!!",B40)),0)
No. of hours Stop due to No Cane	=IF(B44="mill stop!!!",IF(B41>0,IF(B34<[UmfoloziModel.xlsm]Input!$B$25,(([UmfoloziModel.xlsm]Input!$B$25-B34)/[UmfoloziModel.xlsm]Input!$B$25*24)-B25,0),0),0)
No. of hours Stop due to No Cane (Stockpile)	=IF(B46="mill stop!!!",IF(B42>0,IF(B40<[UmfoloziModel.xlsm]Input!$B$25,(([UmfoloziModel.xlsm]Input!$B$25-B40)/[UmfoloziModel.xlsm]Input!$B$25*24)-B26,0),0),0)
No Cane Mill Stop Flag	=IF(B47>0,1,0)
No Cane Mill Stop Flag (Stockpile)	=IF(B48>0,1,0)
Temperature Average (degree C)	25.5 (varies daily)
Percentage Decrease in RV	=100*(1-EXP(-1*(EXP(-9498/(AY3+273.15)+24.1))*Input!$B$15))
Daily RV % Cane	10.42423077
Daily RV % Cane (Stockpile)	=BA3-BA3*(AZ3/100)
Tons RV	=(B51/100)*B34
Tons RV (Stockpile)	=(B52/100)*B40
Return from RV	=B53*[UmfoloziModel.xlsm]Input!$B$10
Return from RV (Stockpile)	=B54*[UmfoloziModel.xlsm]Input!$B$10