AN INTEGRATED SUGARCANE SUPPLY CHAIN MODEL: DEVELOPMENT AND DEMONSTRATION

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Submitted in partial fulfilment of the requirements
for the degree of MSc Engineering

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2006

DISCLAIMER

I wish to certify that the work reported in this dissertation is my own original and unaided work except where specific acknowledgement is made.

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ACKNOWLEDGEMENTS

I extend my sincere gratitude and appreciation to all those who made this masters dissertation possible.

- Dr CN Bezuidenhout, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, for his commitment to supervising the project, ensuring that a suitable standard was met and the work was also enjoyed.
- Prof PWL Lyne, South African Sugarcane Research Institute (SASRI), for his support and guidance throughout the project.
- Mr Steve Davis, Sugar Milling Research Institute (SMRI), for readily assisting in providing technical insight and guidance on modelling sugar milling processes.
- Dr Adrian Wynne, South African Canegrowers Association (SACGA), for providing technical assistance and access to a model which compares the economics of trashing and burning of sugarcane.
- Richard Loubser, SMRI, for providing technical information on sugarcane deterioration and access to a model for estimating the effects of sugarcane quality on factory output.
- The Department of Transport via the Eastern Centre of Transport Development for funding the project.
- The School of Bioresources Engineering for hosting the project and providing infrastructure and support.
- The following people involved at TSB Malelane and Komati Mills: Mr Roelf Venter for organising the case study, Mr Schalk Krieg, Mr Alan Williamson, Mr Clint Vermulen, Mr Nico Stoltz and Mrs Lynie van Staden.
- To the other members of the project steering committee, namely, Dr Abraham Singles (SASRI), Mr Arnoud Wienese (SMRI), Dr Brian Purchase (SMRI), Mr Eddie Meyer (SASRI), Mr Erik Dube (UND), Mr Francois Oberholzer (ICFR), Mr Mark Smith (SASRI), Dr Maurits van den Berg (SASRI) and Mr Paul Schorn (Hullets Sugar LTD).
- To family and friends for encouragement.

ABSTRACT

The South African sugar industry is a large industry which relies on expensive capital equipment to harvest, transport and process sugarcane. An average of 23 million tons of sugarcane are annually supplied to 14 mills from over 2 000 large-scale commercial growers and 48 000 small-scale growers. Supply chain stakeholders can benefit if operations are successfully streamlined. Computer-based mathematical models have been used in other industries to improve supply chains, especially in forestry, and are expected to play an increasingly important role in future planning and management.

Management of sugar supply chains has historically focussed on generating competitive individual supply chain components. However, inter-component optimisation generally disregards many important intra-component interactions. Hence, efficiency improvements may be significantly limited. Integrated supply chain modelling provides a suitable approach for addressing this problem. The aim of this project was to develop and demonstrate, in concept, an integrated supply chain model for the sugar industry. Such a model could be used to address various integrated planning and management problems throughout the supply chain. A review of existing integrated agri-supply chain models was conducted followed by the development of CAPCONN, an integrated sugar supply chain model framework, that incorporate all steps from field to mill back end. CAPCONN estimates sugarcane quality, mill recovery, capacity utilisation and production costs. Bottlenecks are highlighted and the model could contribute towards capacity manipulation for efficiency improvements under different harvesting scenarios.

CAPCONN was demonstrated by analysing a number of scenarios in a mechanisation case study at Komati Mill where sugarcane is currently burned and manually cut. A total of twelve scenarios were compared, including variations in cropping system and time of year. The model framework predicted that a decrease in sugarcane quality and sugar recovery would occur under mechanical harvesting scenarios. Estimated production costs were also higher, even though the transport fleet was significantly reduced. A manually cut green (unburned) harvesting scenario showed a further decrease in sugarcane quality and sugar recovery. Mechanical harvesting during wet weather caused a substantial reduction in supply chain capacity and an increase in production costs. CAPCONN output trends compared favourably with measured and observed data, though the magnitude of the trends should be viewed with caution, since the CAPCONN framework is only a prototype. This shows that it may be a suitable diagnostic framework for analysing and investigating the sugarcane supply chain as a single entity. With further development to a model, the CAPCONN model framework could be used as a strategic planning tool although, one drawback is that a relatively large number of technical inputs are required to run the model.

NOTATION FOR SUPPLY CHAIN COMPONENTS AND VARIABLES

Component	**Symbol**
Harvest	H
Loading	L
Transport	T
Off loading	OL
Preparation	P
Extraction	E
Boiler	B
Exhaustion	X

Variable	**Symbol**	**Units**
Sucrose	S	%
Non-sucrose	NS	%
Fibre	F	%
Ash	A	%
Tops	TS	%
Trash	TSH	%
Stalk	ST	%
Quality or compound % of total produce mass	α	%
Truck payload	ρ	tons
Weekly throughput capacity	C	$t.wk^{-1}$
SC constricting capacity	C_{min}	$t.wk^{-1}$
Throughput rate capacity	γ	$t.hr^{-1}$; $t.day^{-1}$
Operational throughput rate	y	$t.hr^{-1}$; $t.day^{-1}$
Capacity utilisation	CU	%
Effective hours operated	t	$hr.wk^{-1}$
Unavailable operational time	U	$hr.wk^{-1}$
Cost	π	R

Note: Component and variable symbols were combined in the format V_C where V represents the variable symbol and C represents the component symbol.

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1 INTRODUCTION

A supply chain describes the physical flow of resources from procurement through to the consumer. The sugar supply chain is an agri-supply chain, that is comprised of the physical flow of sugarcane between growing, transport and processing components, as well as the processes within individual components (Gigler *et al.*, 2002). According to Creamer (2006), the South African sugar industry generates an average annual revenue of over R5 billion, and this could be increased if operations were successfully streamlined. Streamlining refers to component optimisation which improves sugar quantity and quality, and reduces production costs, and ultimately increases profit. However, co-ordination of South African sugar supply chains, is complicated by the existence of a high number of independent growers, which makes centralised logistic planning solutions difficult (Gaucher *et al.*, 2004). Computer models have been used in many industries to visualise complicated supply chain systems and improve profitability, and are expected to play an increasingly important role in future planning and management.

Management of sugar supply chains worldwide tends to focus on generating competitive individual supply chain components. This inter-component optimisation generally does not consider all the important interactions between components and hence the efficiency of the supply chain may be limited (CSIR, 2004). Integrated supply chain modelling has been recognised as a suitable tool for supply chain planning and system improvement, considering the supply chain as a single entity (Rőnnqvist, 2003). Integration refers to the interlinking of individual supply chain components to form a single component.

This project's hypothesis is that an integrated supply chain model is a suitable and feasible tool for representing supply chain processes and improving efficiencies. The aim of this dissertation is to demonstrate, in concept, that an integrated supply chain model, from the point of harvest to the production of raw sugar, could be developed for the South African sugar industry. The research involved three primary objectives. The first objective was a brief review of existing integrated agri-supply chain models, with a focus on the sugar supply chain. The second objective was the integration of current fragmented knowledge of sugar supply chains into a suitable analytical framework from harvest to raw sugar production. The third objective was to demonstrate this framework as part of a mechanisation case study, which facilitated a theoretical test for the model as well as the investigation of a new and complex industry issue. Depending on the success of the project, the theoretical model framework may later be developed into a model for industry use, by refining inputs and algorithms. The time step for the model was chosen to be one week, therefore the effects of management decisions and system considerations at less than a weekly time step were not included.

2 AN OVERVIEW OF AGRI-FORESTRY SUPPLY CHAIN MODELS

2.1 Introduction

There is a worldwide trend towards greater competitiveness and deregulation in the production and sale of agricultural commodities (Gigler *et al.*, 2002). Existing management methods are not achieving sufficient performance levels, hence new forms of co-ordination are required to improve efficiencies and profitability (Gaucher *et al.*, 2004). There is currently an increased interest in modelling integrated agricultural supply chains, since competitiveness in the world market is more easily achieved by developing a single competitive supply chain unit, compared to the development of competitive individual components (CSIR, 2004). This chapter discusses the use of models in the management and planning of agri-forestry supply chains. Model types and the influence of a planning horizon are reviewed, followed by an overview of existing models for forestry and for agricultural supply chains (other than the sugar supply chain).

2.2 Agri-Forestry Supply Chains

Agri-forestry supply chains describe supply chains for usually perishable produce of agricultural origin (Gigler *et al.*, 2002). Agri-forestry industries typically follow a pyramidal supply structure with many producers supplying raw materials to a few processing facilities (Ainsley Archer *et al.*, 2005). According to Rőnnqvist (2003) every supply chain planning problem needs a model to capture important processes and facilitate system optimisation.

Modelling problems and techniques in agri-supply chains are expected to develop rapidly in the near future as a result of increased pressure for supply chain improvement (CSIR, 2004). Agri-forest supply chain models address management and planning problems over various planning horizons, integrating different combinations of components at different levels of detail (Rőnnqvist, 2003). Components are usually modelled sequentially due to the high level of variable interaction between components.

Numerical models are most commonly used to evaluate different methods for increasing productivity (increasing efficiencies, production and net profit) without expensive and time consuming experimentation, which may not be practically feasible (Barnes *et al.*, 2000). Economic models are usually used to analyse supply chain stakeholder interactions, while Operations Research models optimise physical supply chain problems through mathematical modelling (Gaucher *et al.*, 2004). The disadvantages of mathematical models are that skilled people are required to formulate and interpret them (Thompson, 1997) and that accuracy is limited when physical systems are simplified to a practical modelling level (Loubser, 2002).

2.3 Types of Models Used in Supply Chain Planning

According to Mitchell (2004) the choice of the supply chain model type depends on the nature and complexity of the problem and the required output. The simplest models used in supply chain planning simulate the physical system, while more complex models optimise systems and identify critical factors. Spreadsheet based models are used for simple algebraic modelling and basic optimisation. Scenarios that are too complex to be solved or optimised by a spreadsheet can be formulated into equations and solved by a mathematical solver. Linear programming (LP), integer programming (IP) and non-linear programming (NLP) techniques are used to optimise such equation sets. Mixed integer programming (MIP) combines LP and IP. Simulation models are used to model systems which are too complex to be represented algebraically.

Spreadsheet models make use of a spreadsheet to serve as a framework to store and run algebraic equations, and graph outputs if required. The algebraic processing capability of these models is limited to that of the spreadsheet used. The most popular spreadsheet platform worldwide is MS Excel®. MS Excel® offers convenient data entry and editing and a LP solving option called Solver has recently been included (MacDonald, 2005). Spreadsheets are, however, not considered to be user friendly if they do not have a graphical user interface (Thompson, 1997).

Mathematical solvers are applications that offer a range of advanced algebraic processing and plotting capabilities. An example of a mathematical solver is Matlab® (MathWorks®), which is a high generation computing language and interactive programming environment. Matlab®, an abbreviation of "matrix laboratory", is based on the use of matrices, making it well suited for linear algebra computations. It is used for algorithm development, data analysis and visualization and numerical computation.

LP, IP, MIP and NLP models make use of a specific algebraic solving technique to solve problems of a specific nature. The problem is entered into the model as a series of equations and the model is set to determine the maximum or minimum of the solution space. LP models maximise or minimise a linear objective function subject to constraints (Ioannou, 2004). This technique allows the user to determine the optimal allocation of scarce resources. An advantage of LP models is that risk can be accounted for, allowing a problem to be solved according to a preferred risk level. One of the most popular commercial LP models is LINDO® (Lindo Systems Inc., 2005); (MacDonald, 2005). Linear programming models can include integer variables allowing activities to be either selected or omitted. This process is called integer programming (IP). This is useful for choosing optimal activities and for sequencing activities, which allows phenomena such as economies of scale to be modelled (Lyne, 2005). Integer programming can cope with non-linear inputs, but problems are difficult to solve and often require an additional procedure called column generation to account for large numbers of input variables. Mixed Integer Programming (MIP) is a combination of LP and IP (Rőnnqvist, 2003). Dynamic Programming (DP) is a modelling approach used to solve sequential or multi-stage decision problems. An example of a DP is a series of LP models, where the output of each model becomes the input for the next model. This allows future scenarios to be evaluated and accounted for. Linear programming requires both the objective function and the constraints to be linear. Non-linear programming (NLP) techniques are available for solving LP problems involving non-linear relationships (Lyne, 2005).

Simulation models provide a framework for capturing a physical system as a series of components, allowing the user to view the physical characteristics of the system which are lost in a purely algebraic model. They provide a quick and reliable way of comparing different scenarios in the supply chain, often providing an animation of operations. Parameters such as time delays can be input in histogram form, producing a distribution of outputs, which improves the representation of the system. Models are available for the simulation of discrete and continuous systems or a combination of the two, called hybrid systems (Villani *et al.*, 2004). Higher generation simulation models are capable of optimisation. Simulation helps stakeholders to make decisions by enhancing common knowledge and finding solutions which take all concerns into account (Guilleman *et al.*, 2003). Heuristic procedures can be incorporated into a simulation or optimisation model to obtain a solution quickly. Heuristic procedures generate and search within critical parts of the solution space to reduce solution time, but solutions are near-optimal, rather than exact (Barnes, 1998). One disadvantage of simulation modelling is that it can be difficult to identify which factors produce differences in results (Sonesson and Berlin, 2003).

2.4 Model Planning Horizon

The model planning horizon or timeline refers to the time period over which modelling outputs are generated. It is an important aspect of integrated modelling, as the planning horizon in each component of the supply chain should be matched for the model to be realistic. Table 2.1 shows the terminology for different planning horizons and gives examples of activities within a forestry supply chain context. These terminologies differ between countries (Rőnnqvist, 2003).

Table 2.1 Different planning horizons in forest related supply chains (Rőnnqvist, 2003)

	Category of activity		
Planning level	**Management and harvest**	**Transport and routing**	**Production**
Strategic planning > 5 years	Planting	Road construction and management	Investment planning
Tactical planning 6 months to 5 years	Harvest plan	Road upgrade Machinery utilisation	Annual production planning
Operative planning 1 day to 6 months	Crew scheduling Harvesting	Scheduling	Scheduling
Online planning < 1 day	Windrowing Stacking	Truck dispatching	Process control

Mitchell (2004) states that forest related planning operations are commonly divided into a hierarchy of strategic, tactical and operational plans. Table 2.2 shows the characteristics of each planning horizon. The plans all begin with the current period as the starting point, differing in resolution, accuracy and planning horizon outlook.

Table 2.2 Characteristics of forest related decision problems (Mitchell, 2004)

Characteristics	**Strategic Planning**	**Tactical Planning**	**Operational Planning**
Objective	Resource	Resource acquisition	Execution utilisation
Time Horizon	Long	Middle	Short
Level of Management	Top	Middle	Low
Scope	Broad	Medium	Narrow
Information Source	External and Internal	External and Internal	Internal
Level of Detail	Highly Aggregated	Moderately Aggregate	Very Detailed
Degree of Uncertainty	High	Moderate	Low
Degree of Risk	High	Moderate	Low

2.5 Modelling in Agri-Forestry Industries

Examples of major agricultural and forestry supply chains in South Africa are those which supply fruit, grains, sugar, cotton, meat, wool, forest products and flowers. Production systems in these industries are composed of, at a minimum, a primary production component, a processing component and a wholesale component (Ainsley Archer *et al.*, 2005). Forestry and agri-supply chain models are discussed in the following two sections.

2.5.1 Forestry supply chain models

Rőnnqvist (2003) and Mitchell (2004) describe a variety of optimisation models used in the European, Chilean, New Zealand and Australian forestry industries for operative, tactical and strategic planning. Large amounts of data are required for the formulation of these models, which are usually obtained from GIS databases. Typically, the models only describe a small portion of the supply chain. A wide array of software tools are used, and there is not, as yet, an industry standard.

Linear Programming (LP) models are used for strategic planning of planting, harvesting and scheduling. Dynamic Programming (DP) has been used extensively in operational planning of activities, such as bucking (logging), where information from markets and production plants controls harvesting operations (Rőnnqvist, 2003). MIP is used for tactical planning of harvest and road building and upgrading activities, where both integer and non-integer variables are involved. Forestry problems are also often modelled using IP models, while LP models and heuristics are used in produce transportation planning at an operational level. Simulation modelling is most commonly used for truck scheduling. Moving into the mill, production optimisation models are used to evaluate scenarios, but not to make strategic and tactical decisions, due to the complexity of interactions. Operational planning in sawmills is performed by LP and DP. Pulp and paper mill tactical and operative planning are usually integrated with transport. Online planning of process control is usually done by single loop optimisation models (Rőnnqvist, 2003).

While most models only consider a small portion of the supply chain, some attempts have been made at integrating the full supply chain into a single model. According to Rőnnqvist (2003) there is a general opinion in the forestry industry that efficiency improvements lie in improved integration between wood flow components with a focus on customer orientation. Bredstrom *et al.* (2004) modelled the harvest, transport, production, storage and distribution of a large pulp producer with five mills using a large MIP model. A layout of the timber supply chain model is shown in Figure 2.1. A column generation component was used for network planning while another component considers daily decisions. Bredstrom and Rőnnqvist (2002) developed a logistic support system for a large Swedish pulp producer. They divided the supply chain into a pulp production component and a distribution component. MIP was used to optimise partial problems within these two components. According to Carlsson and Rőnnqvist (2005), integrated frameworks such as these are essential for identifying the rank of importance of factors in effective supply chain operation.

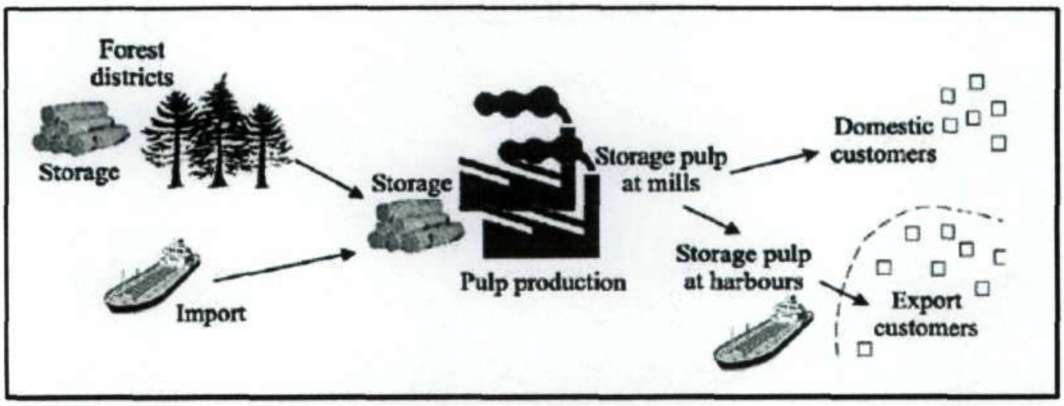

Figure 2.1 The timber supply chain components modelled by Bredstrom *et al.* (2004)

2.5.2 Agricultural supply chain modelling

The literature shows that modelling is applied to a variety of agri-supply chain problems (Gigler *et al.*, 2002). These range from models of individual components to models of a series of integrated components. Figure 2.2 is an example of a pea supply chain.

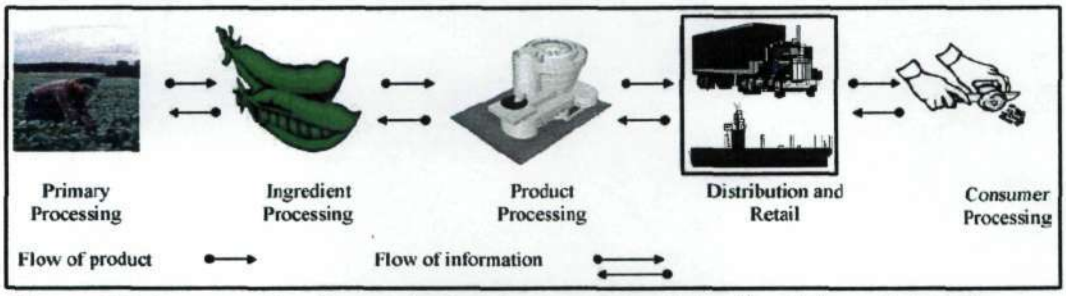

Figure 2.2 An example of an agricultural pea supply chain (Apaiah *et al.*, 2005)

Models for agri-supply chains most commonly consist of crop models, scheduling models, and overall supply chain models. Crop growth models are usually stand-alone due to the complexity of biological systems. Simulation modelling is most commonly used when there is a need to capture complex system interactions. Examples of commercial models are APSIM (APSRU, 2005), ACRU (Schulze, 2005) and The

Decision Support System for Agrotechnology Transfer (DSSAT) (ICASA, 2005), are used for systems analysis on a range of crops. ACRU is used to simulate crop yield while APSIM includes additional features of optimisation procedures and an economic module (McCown *et al.*, 1994). DSSAT is a crop simulation model used in over 100 countries for over 15 years and uses the CANEGRO model to simulate sugarcane growth (Hartkamp *et al.*, 2004), (Inman-Bamber and Kiker, 1997).

Customised simulation models have been developed for unique applications. An example is the model developed by Haverkort and van Haren (1998) for potato growth simulation. The model determined worldwide optimum production based on optimal variety and location combinations. MIP has also been used for the optimisation of animal product operations, which typically involve fewer variables compared to crop operations. Wade and Fadel (1995) used a MIP to optimise caviar and meat production. The model was moderately complex demonstrating economic feasibility and generating an optimal production schedule.

Scheduling models usually run from farm gate to production or consumption. Modelling is most commonly done by MIP and DP. Gigler *et al.* (2002) describe a range of MIP's developed to optimise agri-supply routes in the Netherlands. They present a method to optimise agri-chains using DP. The model determines the least integral cost routes defining which process (e.g. harvest, transport, and factory) is assigned to the available resources (produce, vehicles) under required constraints. Applications to banana and willow chip agri-chains are also discussed. The banana supply chain model includes harvest, transport, wholesale activities, truck distribution and retail activities to meet the consumer at target ripeness.

Supply chain problems, such as economic and environmental sustainability analysis have been addressed by LP (van Calker *et al.*, 2004) and simulation modelling (Sonesson and Berlin, 2003). Various models have been used in supply chain infrastructure capacity evaluation. CSIR (2004) used multiple models to assess capacity in a National Fruit Logistics Infrastructure Study in South Africa. Simulation models were used for capacity utilisation investigations of the Durban and Cape Town fresh produce terminals. A multi-commodity produce flow optimisation model was used to determine the national network flow and storage capacities.

In the future, modelling is expected to play a greater role in supply chain planning as pressures on supply chain performance increase. A wide range of models is available. Model selection depends on the nature of the problem, complexity and the required output. The planning horizon needs to be considered in order to synchronise supply chain components. Relatively simple problems are modelled by spreadsheet applications while more complex problems, involving many variables, are simulated. Optimisation models such as LP, DP, MIP and mathematical solvers determine optimal variable combinations. Trends in the literature show that the agronomic component is most commonly simulated and MIP is used for transport scheduling. No models of agri-supply chain processing plants were reviewed. Furthermore, no comprehensive models of integrated agri-supply chains, from primary production through to the consumer, were found. Value chain models account for human impacts on the supply chain. Those used in agri-chains were generally supply chain models adapted to include factors such as management decisions (Yaibuathet *et al.*, 2001).

2.6 Conclusions

Mathematical models provide a basis for system evaluation and decision support. Models are used for dealing with a range of planning problems. Operational and online planning problems are usually solved by stand-alone models that consider only the process of concern. Strategic and tactical planning problems have previously been solved by models that tend to focus on individual supply chain components, often at the expense of overall optimisation and therefore international competitiveness of the industry.

A range of models are used in agri-forest operations. These models address planning problems in physical systems with a range of complexity, different planning horizons and various levels of integration. Models are primarily used to represent physical systems and more advanced models are used to optimise and identify critical factors. The choice of model depends on the nature of the supply chain problem, the required modelling complexity and output. Simple problems are usually formulated into spreadsheet and algebraic models. This includes problems which are straightforward by nature and those which have been simplified by considering only the dominant factors and variables. Such models would typically be applicable for single component analysis or estimating solutions to large scale strategic and tactical planning problems. More complex problems requiring optimisation are solved by LP and DP. These methods have been used extensively in forestry industries worldwide (Rőnnqvist, 2003), and are applicable for optimisation scenarios such as optimising capacity investment subject to cost. Simulation models are used for modelling systems involving a high level of variable interaction and would be suitable for an operational transport analysis and integrated component analysis.

3 A REVIEW OF SUGAR SUPPLY CHAIN MODELS

In Chapter 2 some modelling concepts and a range of agri-forest supply chains were reviewed. This chapter covers modelling of the sugar supply chain. A description of the sugar supply chain system was firstly provided and a range of sugar supply chain models were then discussed. The models ranged from individual component models to integrated models of the full supply chain.

3.1 Introduction

Supply chain management in the sugar industry is concerned with co-ordinating stakeholders to regulate the quantity and quality of produce flow from the farmer to the miller and onto the consumer. Management is under increasing pressure to increase productivity due to factors such as the drop in the international sugar price over the past few years (Guilleman *et al.*, 2003).

According to Salassi *et al.* (1999), increasing input costs are narrowing profit margins and the future sustainability of sugar industries lies in finding ways to produce sugar more economically. Noqueira *et al.* (2000) states that a major factor causing the sugar price drop is the substitution of natural sugar by artificial or laboratory produced sugar. Cox (2005) states that the use of modern technology and the advantage of high yields and economies of scale enable major producers, such as Brazil, to sell sugar at a relatively low price while ensuring market security through diversification into activities such as ethanol production. Noqueira *et al.* (2000) and Cox (2005) argue that investigations into diversification options in the sugar industry are required in order to remain globally competitive. Diversification options include the production of green energy and ethanol. Animal feed options have also been researched.

3.2 A Review of the South African Sugar Supply Chain Physical System

The sugar supply chain is a non-integrated system. However, the activities in each component often interact significantly with the operation of components following on from the respective component. Processes need to be effectively streamlined and integrated in order to achieve a reliable and efficient sugarcane flow. This can only be achieved through a sound understanding of the full system. Figure 3.1 shows the main components of a simplified sugar supply chain.

The planning horizons for sugarcane production correspond to those shown in Table 2.1. Variations are expected in the actual length of planning horizons as the ratoon lengths of sugarcane are significantly less than those characteristic of the forestry industry.

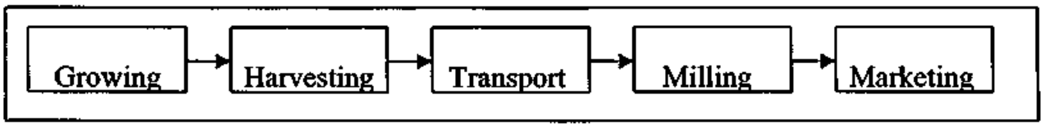

Figure 3.1 Main sugar supply chain components (Higgins *et al.*, 2004)

3.2.1 Field to mill components

The sugar supply chain essentially begins with the growing of sugarcane. Various sugarcane varieties are used depending on climate and soil conditions. In South Africa areas north of the Umfolozi River generally require irrigation, while southern areas generally support rain fed sugarcane or a combination of both.

The composition of sugarcane varies throughout the plant life cycle, and also throughout the harvest season, which runs for roughly 10 months from April to December. Commercial sugarcane entering the mill is typically composed of soluble sucrose ±12%, non-sucrose ±2%, insoluble fibre ±14% and ash ±2% as well as water ±70%. Normally, fibre content is at its maximum in the early season (April – May), sucrose content peaks at midseason in winter (July – August), and non-sucrose peaks at the end of the season (November to December). The term ash refers to insoluble non-carbon compounds of which the major component is usually soil.

The most important components of non-sucrose are those which reduce sucrose recovery. These are largely soluble non-carbons (also termed soluble ash), which limit crystal formation. Non-sucrose also includes viscosity enhancing substances, generally known as gums, starches and dextrans. Once harvested, sugarcane rapidly deteriorates, during which sucrose decomposes to form other compounds. Deterioration is accompanied by an increase in non-sucrose which is generally proportional to the loss of sucrose (*pers. comm.*[1]). It is therefore desirable to minimise the harvest to crush delay (HTCD). Deterioration is largely a function of time, temperature, humidity, variety and degree of sugarcane damage (billet or whole stalk) (Lionnet, 1998). Non-sucrose is also inherent to drought stressed sugarcane and sugarcane with split stalks. Two other processes which occur after harvesting are a loss in mass due to water loss (mainly evaporation), and respiration, which refers to the oxidation of sugars to produce heat, water and $C0_2$.

Sugarcane age at harvest ranges from 12 to 24 months, depending on the climatic potential and attempts to mitigate against pests. Worldwide, it is estimated that 50% of sugarcane is burned before harvest (Meyer *et al.*, 2005). According to Meyer and Fenwick (2003) 80% of sugarcane in South Africa is burned before harvesting. This reduces mill trash levels and improves harvest rate, although burning is believed to significantly increase maintenance costs in mechanical harvesting due to the abrasive nature of carbon (*pers. comm.*[2]). The use of mechanical harvesting is expected to increase worldwide. This is largely due to a decrease in the availability and productivity of manual cutters (de Beer and Purchase, 1999). Burning enables higher utilisation of transport equipment as sugarcane bulk densities are higher and less money is spent on carting trash. Burning, however, impacts on sugarcane deterioration as it lengthens the HTCD. Burning, especially under hot conditions, causes tissue damage by cracking open stalks. As a result, deterioration is more rapid. For delays under 20 hours deterioration is similar to that of green sugarcane since spores and bacteria are destroyed in burning, which delays the onset of deterioration (Lionnet, 1996). After 20 hours, however, the deterioration rate of burned sugarcane is significantly higher compared to green sugarcane. In South Africa the current average HTCD is ±160 hours (*pers. comm.*[3]).

According to Meyer (1999) 80% of sugarcane worldwide is cut manually. In South Africa 98% of sugarcane is manually harvested and a variety of manual harvesting

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[2] L. van Staden, Harvesting contractor, Komatipoort, South Africa, March 2006
[3] P.W. Lyne, Agricultural Engineer, SASRI, Mount Edgecombe, South Africa, November 2006

techniques have been implemented (Langton, 2005). A small proportion of the industry is mechanised, using chopper harvesters which are able to load while cutting, and hence eliminate the need for loading equipment. Different sugarcane varieties have different degrees of hardness, which impacts on the ease and rate of cutting. Manually cut sugarcane is laid in windrows, stacked or bundled and then extracted by haulage vehicles (Langton, 2005). "Lodging" refers to the case when mature sugarcane falls over, often as a result of wind, high rainfall, structural weakness or saturated soils. Lodged sugarcane is difficult to cut manually and is more easily harvested mechanically. Manually harvested lodged sugarcane will also reduce payloads as the stalks are usually curved which reduces the bulk density of the product.

The composition of the harvested product has a significant impact on components further down the chain. Prior to the mill, sugarcane composition mainly impacts on harvesting, loading rate and payload as trash occupies volume hence displacing stalks. In the mill, different processes become more significant and complicated. Approximately 75% of the plant is stalk, which contains sucrose, non-sucrose, fibre and ash, and the remainder consists of tops and trash. Tops carry a high colour content that darkens the colour of sugar and also have low sucrose content which makes them non profitable to transport. Most tops are therefore removed during harvesting. Trash also adds a significant amount of colour and fibre to sugarcane (Purchase and de Boer, 1999). Research by Scott (1977) in Australia showed a 1% increase in trash caused a 2.75% increase in fibre content. Fibre has a significant impact on the mill and is the primary regulator of throughput in the mill front end (Kent *et al.*, 1999). Purchase and de Boer (1999) showed that crushing sugarcane with tops and trash reduced sucrose throughput from 25 to 16 tons per hour. The reduction in throughput described above is a result of a combination of processes in different parts of the mill. Fibre will reduce throughput, it will carry sucrose away in extraction where it acts as a sponge, and its colour and impurities will create processing difficulties in the mill back end (ESR, 2005).

One of the most significant determinants of product composition is the performance of the harvesting method. Hence it is important to have well trained labour. Mechanical harvesters can pick up large amounts of soil, especially in wet conditions with infield ridging. Trash levels also increase when mechanical harvesting is used, and a loss of harvested sugarcane occurs in the cleaning system (ESR, 2005). A compromise between sugarcane losses and trash levels needs to be met as higher extractor fan speeds remove more trash, but also increases sugarcane losses as billets are blown out with the trash (Meyer, 1999). Deterioration of mechanically harvested sugarcane is higher as a result of a greater surface area of sugarcane exposed to air. Lionett (1998) showed that cleanly cut burned billets on average lost 0.14% of sucrose per hour, while mutilated billets from older and un-serviced machines lost 0.23%. Furthermore, poor operation and stool damage of mechanically harvested sugarcane reduces the long term yield. Soil compaction can be significant for both harvesters and haulage vehicles travelling infield. Meyer (1999) outlines the impacts of soil compaction on yield, showing that yields can be halved in cases of severe row and inter-row compaction.

Transport in the South African sugar industry generally involves a primary and secondary component. Tractors are used for primary and trucks for secondary haulage. Some operators do haul directly from field to mill, depending on haulage distance and field grades. In the field, windrowed sugarcane is loaded mechanically by infield loaders. Bundled sugarcane is loaded by hand or stacked and loaded by self loading trailers. Transloading zones typically use mechanical bell loaders or transloading cranes. Transport involves a significant proportion of the total supply chain production cost (Giles, 2004). The main objective of the loading and transport components is to maintain a constant supply to the mill at minimal expense. This is achieved through capacity planning to determine the required capacity of equipment. Scheduling is a tool for the use of equipment. System delays arise due to the difference in the cycle times of harvest, load and transport operations. In order to minimise delays, cycle times need to be matched (Barnes *et al.*, 2000). Unscheduled and overcapitalised systems both result in inconsistent throughput, low equipment utilisation and high cost.

Sugarcane receiving systems differ between mills. Trucks arriving at the mill are weighed and then offloaded. At most mills, offloading occurs directly onto the mill spiller table, which feeds sugarcane into the mill front end. Some mills may use a sugarcane stockpile as a buffer to ensure consistent supply into the mill, especially on Sundays and during no-cane stops.

3.2.2 A description of mill processes

Pillay, 2005 describes the two stage preparation process. Once on the spiller table, the sugarcane is conveyed to a set of knives. The knives billet the sugarcane and a shredder then pulverises the billets. Shredding breaks open cells, which allows brix (sucrose and non-sucrose) to be extracted. Some mills include a rock and trash removal system as rocks can damage preparation equipment and soil and trash impact significantly on mill preparation and extraction efficiency. Sugarcane preparation may become a bottleneck in the beginning of the season, when fibre levels are high. Sugarcane hardness, which varies with varieties, lowers the throughput capacity and increases maintenance costs of mill preparation equipment. Similarly, billeted sugarcane is more easily crushed, provided trash levels are not significantly increased. Hence it can increase throughput capacity and possibly decrease equipment maintenance cost.

After preparation, a sample of sugarcane is taken to estimate the sugarcane composition and calculate the value of the sugarcane using the Recoverable Value (RV) formula, (Murray, 2002). The RV formula accounts for the effect of non-sucrose and fibre on extraction. Losses to bagasse are a function of fibre level and losses to molasses are a function of non-sucrose level.

Extraction technology has moved from mill tandems to diffusers, which wash out brix (soluble sucrose and non-sucrose) using water. This process is called imbibition. Older mills use mill tandems to squeeze out brix and use imbibition as well. Mill tandem maintenance costs are 75% higher than that of a diffuser. Once extracted the brix enters a mixed juice tank while the remaining fibre (bagasse) is stored or burned to heat the boilers. Sucrose extraction efficiency is a function of many variables. Major regulators are fibre %, imbibition %, sucrose % and produce throughput rate. The Corrected Reduced Extraction (CRE) formula calculates changes in a reference extraction due to variations in fibre and sucrose. Other factors impacting on extraction are soil and trash (Cárdenas and Diez, 1993). Diffuser throughput capacity is usually limited by the dewatering mill's fibre throughput capacity, which removes water from bagasse (fibre) before it exits the dewatering mill (*pers. comm.*[4]). However, diffusers do require a minimum fibre amount to operate effectively (Pillay, 2005).

Processes after extraction are primarily driven by steam (*pers. comm.*[4]) which is provided by the boilers which are started on coal and then often run on bagasse. In some mills high soil levels regulate mill throughput capacity by extinguishing boiler fires. Purchase and de Boer (1999) state that in milling tandems, 50% of the soil entering the mill passes through into the boiler, while in a diffuser this amounts to 90%. Boilers involve a high maintenance cost of which a large component entails removing soil. It can be concluded that soil has a significant effect on the mill front end capacity. Soil also increases maintenance costs associated with gear boxes and wear on chains (Purchase and de Boer, 1999). Purchase and de Boer (1999) estimate a maintenance cost of 100 $R.ton^{-1}$ of soil passing through the mill. Soil levels are largely related to weather conditions and the harvest and loading methods used. This indicates the integrated relationship between supply chain components.

The first process after extraction is the heating and liming of the mixed juice to remove part of the soluble ash and to manage the pH level. Once in the mill the sucrose deterioration process is primarily in the form of inversion to non-sucrose, which is managed through pH management. The mixed juice enters a clarifier, which removes mud to form a clear neutral juice. Thereafter, the juice enters the evaporator which boils off water, and hence increases the brix concentration. The following components are the pans, crystallisers and centrifuges which usually operate in three stages, namely the A, B and C stations. The pans grow sugar crystals under boiling, the crystallisers continue crystal growth under cooling and the centrifuges separate crystals from the molasses. The A-Pan extracts the majority of the sugar (approx 34%) and usually forms the bottleneck in the mill during the mid season, when sucrose content peaks. The B-Pan is used to form seed crystals which are fed back into the A-Pan. Once the mixture reaches the C-Pan the sucrose content has been significantly reduced. Here viscous enhancing substances such as starches gums and dextrans limit crystallisation and may even cause solidification. The C-Pan therefore often forms the bottleneck in the mill when non-sucrose peaks and this normally occurs in late season (Pillay, 2005).

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[4] S. Davis, Mill Process Engineer, SMRI, Durban, South Africa, January 2006

The conversion of sucrose to crystals in the A, B and C stations is termed exhaustion. This process is primarily affected by soluble ash and viscous enhancing substances. These substances prevent crystallisation by bonding to crystal surfaces. Relatively high viscosities created by certain non-sucrose compounds also retard crystal formation and crystal extraction. Crystals are often washed to reduce colour, which increases value at the expense of sugar loss.

As in all businesses, sugar mills seek to maximise profit. This is normally achieved through managing three key principles, namely throughput, sugar recovery and quality. Throughput needs to be consistent as the mill is most efficient under an even throughput. Higher recovery values mean that more sugar is extracted. Hence, it is desirable to maximise recovery. Quality refers to both produce and sugar quality. Produce quality describes impurity levels in the produce, which ultimately determines sugar quality. Sugar quality refers to the properties (crystal size and colour) of the final product. A balance needs to be found between throughput, recovery, and quality, the ratio of which depends on the cost and ultimately the profit involved.

This section has provided insight into the integrated systems comprising the sugar supply chain. Harvesting, loading, transport and mill yard management practices can significantly influence downstream processes. The problem concerning optimisation is complex and requires an integrated material handling systems analysis, supported by sound economic and sustainable management approaches. Mathematical modelling provides a suitable platform to address the problem and the remainder of this chapter discusses models developed for the sugar supply chain.

3.3 Models for Individual Sugar Supply Chain Components

Models developed for individual supply chain components generally fall into one of three categories; growth, transport and milling. They are usually developed to address particular planning problems within each component and therefore simplify the physical system to involve key variables and processes of the specific problem. Although these models are not strictly supply chain models as they do not integrate components, they do form a supply chain model when linked. Modelling of the full supply chain has been described as an intractable task due to high complexity and component interaction.

Running sub-models in parallel as a single application is seen as the best integrated modelling approach (Terzi and Cavalieri, 2003).

3.3.1 Modelling of sugarcane growth

Existing sugarcane growth models are most commonly simulation models. Agronomic planning problems addressed by these models include optimal variety location, determination of optimal harvest time and growth simulation for sustainability and yield estimation. le Gal (2005) describes a modelling project to determine an optimal harvest plan for the Sezela sugar mill region using simulation, based on the seasonal quality variation of coastal and inland sugarcane. The model could also aid in assessing new strategic issues, such as variety selection for diversification into cogeneration and ethanol production. The MAGI simulation software package described in Section 3.4 was used. Historical yield and sugarcane quality curves obtained from Sezela mill data are the primary inputs. Cheeroo-Nayamuth *et al.* (2000) developed a model to estimate sugar yields in the Mauritian sugar industry. An assessment of potential and attainable yield (potential yield being attainable yield limited by water availability) was needed for management and irrigation investment decisions, as high spatial and temporal climate variability were hindering optimal decision making. The APSIM-Sugar model was used to show the difference between actual and attainable yield and to provide a means to reduce the difference between the two. Complex crop growth simulation models, such as APSIM, are composed of sub models or modules which simulate specific environmental processes or cycles. These modules are often updated, an example being the simulation of the nitrogen cycle by Thorburn *et al.* (2005). Nitrogen is fundamental to the formation of biomass and forms a substantial input cost for commercial sugarcane farms. The complex nitrogen cycle was simulated to gain insight into the effects of climate, soil and plant characteristics on nitrogen accumulation. The model provided new insight into nitrogen dynamics and may be incorporated into growth simulations.

3.3.2 Optimisation of sugarcane harvesting

Sugarcane harvesting involves the cutting and removal of burned or green sugarcane. The harvesting method depends on the terrain, harvesting cost and whether the sugarcane is burned or trashed. The literature shows that mechanical harvesting (billeted and whole stalk) is the principal technology used by sugar producers such as The USA and Australia (Salassi and Champagne, 1998) (Higgins *et al.*, 2004).

Optimising harvest schedules is a well researched field. It involves a high level of interaction with transport schedules and mill operation. Higgins *et al.* (1998) developed an LP model which determines the optimum harvest schedule, considering spatial and temporal yield variations in Australia. These variations make it difficult to determine functional relationships between yield and a harvest date. The model's objective function is to maximise net revenue over a planning horizon subject to capacity and cost constraints. The results showed there are potential gains for optimising harvest date. Higgins and Muchow (2003) continued with the concept by developing an IP model to optimise the harvest date and ratoon cycle with a whole industry approach. The model investigated the potential benefits of an optimal harvest plan accounting for spatial and temporal sugarcane quality variation. The model suggested that substantial savings could be made without any capital investment.

A similar study was made by Salassi *et al.* (1999) in Louisiana, USA. A complex LP model was developed to predict stalk mass and sucrose content based on present and historic climatic and crop data. The sucrose prediction component showed that sucrose content was highest when the plant was mature and that sucrose content curves differed between varieties and ratoon cycles. Older ratoon cycles typically reach maturity faster than newly planted sugarcane and should therefore be harvested at a younger age. Chemical ripeners add a new dynamic to sucrose curves and the feasibility of the technology can be assessed with such a model. With consistent and accurate sucrose curves the harvest schedules can be optimised. The modelling concept was obtained from agronomic LP, IP, Bayesian and Tabu search models used in the forestry industry and is economically based. Yield is predicted and an optimal single-season daily harvesting schedule is selected by minimising harvest cost. Reasonable sucrose yield estimates were obtained in a case study. Future development plans include the implementation of Geographic Information Systems (GIS) which could also be used for fertility programs, weed control programs and replanting decisions.

Once a harvest plan has been formulated the next planning problem is the optimisation of the harvesting process. Salassi and Champagne (1998) describe a spreadsheet model developed to estimate equipment requirements and costs for mechanical harvesting in the Louisiana sugar industry. The model consists of a multi page spreadsheet with macros for user input and output. The model considers whole stalk and chopper harvesters. The loading and transport costs associated with each harvester are also included. The inter-connected nature of the model indicates that harvest and transport are interlinked and that they should not be considered separately.

3.3.3 Optimisation of sugarcane transport

Sugarcane transport from field to mill is costly and involves many interlinked variables. According to Milan *et al.* (2005) sugarcane transport costs are the largest single component costs in raw sugar production. In the Australian and South African sugar industries transport costs amount to 25% and 20% of total production costs, respectively (Higgins and Muchow, 2003); (Giles, 2004).

Infrastructure design addresses road network layout and zone positioning. Rőnnqvist *et al.* (1999) used IP to determine optimum facility location, a principle which could be applied to sugarcane loading zone positioning in South Africa. Mathematical algorithms have been used by Bezuidenhout *et al.* (2004) to solve a similar problem. He determined optimal loading zone positions based on fixed and variable road costs for tractor and truck transport.

Scheduling is concerned with finding the least cost combination of transport units, routes and departure times. A variety of commercial scheduling programs are available and various programs have been developed for specific industries. Giles *et al.* (2005) uses a computer based vehicle scheduling program to assess transport capacity requirements at a sugar mill in Sezela, South Africa. The model showed that the transport system was 60% overcapitalised.

An LP model was formulated by Ioannou (2004) for determining the optimal sugar distribution practices for a large sugar producer in Greece. The model is economically based with an objective function of cost minimisation. A substantial number of variables were considered including storage capacities, production and distribution facilities and actual flow patterns. The model showed that significant savings were attainable through optimal planning of internode transfers, without drastic restructuring of logistic operations. The model, combined with MS Excel procedures, forms part of a Decision Support System.

3.3.4 Optimisation of sugarcane milling

Sugar milling involves the processing of sugarcane into raw sugar. A simplified process diagram is shown in Figure 3.2. A variety of models are used for planning and management of sugar mill operations. Mill optimisation is difficult due to the system complexity involving feedbacks and the presence of both discrete and continuous processes (Villani *et al.*, 2004).

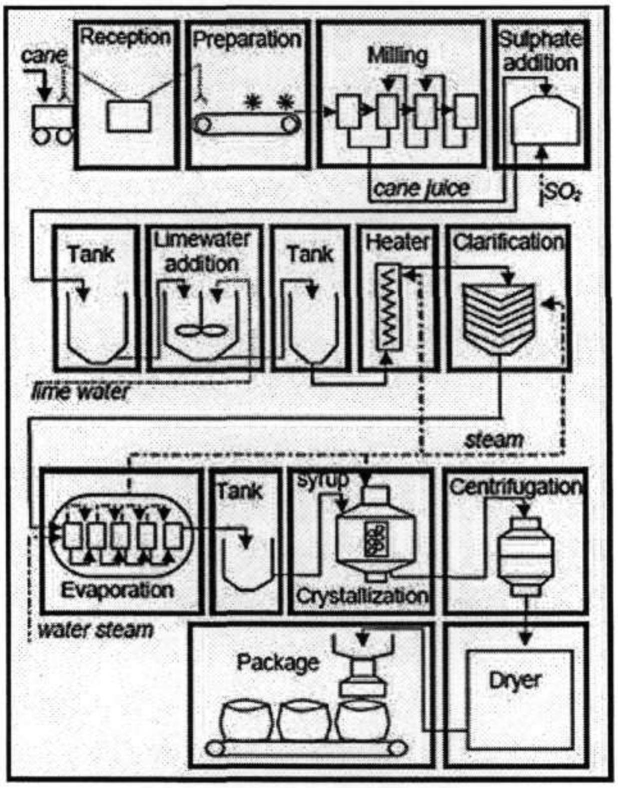

Figure 3.2 Simplified sugar mill process diagram (Villani *et al.*, 2004)

Simulation models are often used in mill planning and management. An example is the Sugars^{TM} model which was developed in the ASPENTECH platform specifically for sugar mills (Alvarez *et al.*, 2001). A mill is constructed through a drag-drop process providing a means of quick customised model construction. The model simulates heat and mass balances and assesses the impacts of process modification. Sugars™ was developed in the US and has been used worldwide. Another mill modelling approach is equation based simulation using programs such as the ASPENTECH Speedup™ platform. This has the advantage of flexibility, but requires knowledge of the program and investigations to formulate inter-process relationships. Speedup™ has the option of dynamic modelling (Thompson, 1997). Models of specific mill components are developed to gain insight into operation and if required, control the processes. An example of such a model is the mathematical model developed by Cadet *et al.* (1999) for mill evaporators. Evaporator control is considered to be of highest importance due to its effect on sugar quality and high energy consumption. The model was validated and implemented in a non-linear control structure.

3.4 Integrated Sugar Supply Chain Models

Stakeholders in the sugar supply chain are starting to recognise the importance of integrated supply chain management, which considers growing, harvesting, transport and processing as a single entity. This enables fundamental strategic and tactical planning problems to be addressed. Gaucher *et al.* (2004) note that joint decision making between several sugar supply chain stakeholders yields higher profits for the whole chain. According to Higgins *et al.* (2004), integrated modelling creates new opportunities for efficiency gains. Higgins and Muchow (2003) state that a whole-system approach needs to be made as component based improvements limit industry profitability. However, the increase in complexity when integrating supply chain components limits the construction of a rigorous model representing all processes in detail. According to Loubser (2002) caution should be taken when integrating components so that simplifications do not reduce the reliability of the model. For operational planning, growing and milling are usually modelled as stand alone components while harvesting and transport are often integrated due to the high interaction between them and high losses resulting from inefficiencies.

The literature shows that integrated harvest and transport models commonly consist of simulation models used for harvester and truck scheduling. For example, an integrated harvest and transport MIP model was developed by Milan *et al.* (2005) for the Cuban sugar industry. The objective function represented sugarcane extraction and transport costs. The model dimensions included a continuous mill supply, harvester selection, vehicle selection and routing. The model proved to be effective in reducing transport cost, combining road and rail, and provided daily harvest and transport schedules.

Barnes *et al.* (2000) describe a discrete simulation model developed to evaluate methods to reduce HTCD in the Sezela mill supply region in South Africa. Altered burning schedules, harvesting groups and delivery schedules were investigated using the ARENA simulation model. All combinations of operations from cutting through to mill feed were stochastically simulated. The various operations are shown in Figure 3.3.

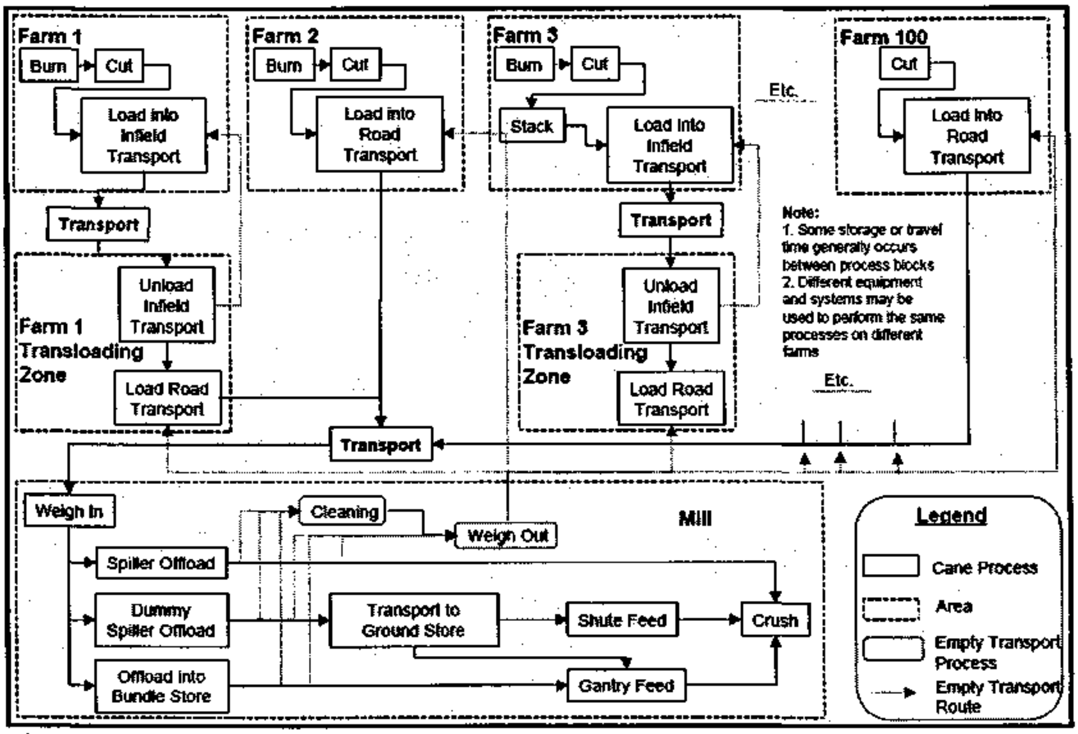

Figure 3.3 Model harvest and delivery system structure (Barnes *et al.*, 2000)

The model was validated by a comparison between simulated and observed data. It proved to be successful, showing that the largest delays occur when burnt sugarcane stands uncut and in transloading and mill stockpiles. One advantage of simulation models, such as this one, is that the model can be adjusted to simulate other mill areas.

Higgins *et al.* (2004) developed an integrated model of sugarcane harvest and transport processes in the Australian sugar industry. Industry regulations were limiting efficiencies (e.g. machinery overcapitalisation) and a model was needed to estimate production cost reduction. Previously, research had only been done on specific components, resulting in technical efficiency for individual components (*i.e.* variety selection, farming practice, harvesting and transport). Research into the integration of harvesting and transport components is now regarded as one of the highest priorities in the Australian sugar industry (Higgins *et al.*, 2004). The first step in the construction of the model was to identify the key drivers and links within the chain. This revealed components representing key activities, major managerial decisions and those conducive to being modelled. These were combined into interrelated modules which could be optimised as one system, shown in Figure 3.4. A financial module was used to keep decisions focused on cost reduction, for example by ensuring transport costs are minimised, but not at the expense of mill delivery rate. The model was applied in two mill areas. The results justified further model development and additional research into change management.

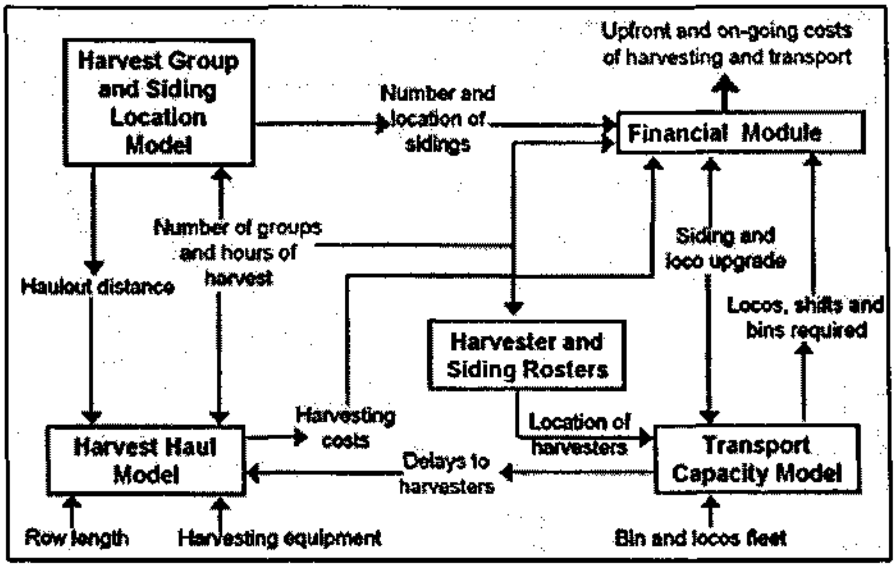

Figure 3.4 Modelling framework showing modules and key links in a sugar supply chain in Australia (Higgins *et al.*, 2004)

Higgins and Davies (2005) describe the harvesting and haulage component of the above model in further detail. They state that optimisation of the full harvest system with such a model is an intractable task. The model harvesting component determines the required haulage capacity. Smaller harvest times place larger demands on harvest capacity and transport systems, and result in longer queuing times. This queuing time reduces the utilisation of transport units. The model determines the number of locomotives and shifts required, the number of bins to deliver from field to railway siding and the harvesting delay while waiting for bins. It is a stochastic simulation model which has the advantages of flexibility and ease of application and integration over optimisation models which produce transport schedules. The model was used for medium to long term (tactical to strategic) planning, running with fifteen minute time steps for simulation of harvester and bin activity. The model was applied to a case study region and the results motivated an increase in harvest time window from 12 to 18 hours and a staggered harvest start time. Further developments will be made by integrating the model with other harvest transport models to simulate impacts on other industry scenarios.

Sugarcane supply scheduling was modelled in MS Excel by Guilleman *et al.* (2003) at a relatively low technical level to assess the potential to improve mill area profitability in the Sezela region, South Africa. This shows that the complex system can be represented by a few key variables, summarised in Table 3.1.

Table 3.1 Model simulation parameters and variables (Guilleman *et al.*, 2003)

	Production units	**Hauliers**	**Mill**
Parameters	Total crop Harvest capacity RV curves	Transport capacity: • Trucks per day • Trips per day • Days worked per week • Average payload	Crush capacity: • Scheduled stops • Breakdown rate • Cane handling capacity • Fibre handling capacity • Non-sucrose handling capacity • Brix handling capacity
Variables	Weekly DRD		Opening or closing date

The model represented a demand driven system, beginning with the mill crushing capacity which is then used to determine the sugarcane delivery rate. Crush capacity is based on sugarcane handling capacity, which ignores quality variations. Crush capacity can also be based on fibre, non-sucrose and brix handling capacities which are quality-dependent. The number of trucks required was estimated by summing the tons per vehicle per trip per day. Sugarcane was sourced from production units, which represent homogenous supply zones characterised by rainfall and temperature. These are linked to mill sugarcane quality records. The model results showed that supply zoning and making delivery schedules according to quality could increase total production, with a profit for both growers and millers.

Most of the models reviewed optimise transport schedules and vehicle requirements with the objective of minimising cost. However, efficiencies can only be determined if vehicle utilisation is known. A model was developed by Arjona *et al.* (2001) for this purpose in the Mexican sugar industry. A discrete event simulation model of harvest and transport systems was developed to assess the problem of machinery overcapitalisation and underutilisation. Mill operations were also simulated to gain insight into mill yard bottlenecks. The model showed that less machinery, operated more efficiently, could maintain production levels and that the inefficiencies result mainly from an inability to manage the complex system.

Integrated modelling of growing, transport and milling involves the development of a single simplified model or the integration of sub models. Ainsley Archer *et al.* (2005) integrated sub models in a sugar supply chain model framework for the Australian sugar industry. They state that the Australian sugar industry was investigating avenues for diversification in order to reduce risk and increase sustainability as a result of a general devaluation of the Australian dollar. Leading sugar industries, such as Brazil, have shown the advantages of diversification into ethanol production, which enables them to sell either sugar or ethanol depending on international market prices. The biophysical, logistical and processing domains are integrated into one model. The model was used to address the issues of reducing risks of quality and quantity, capturing efficiencies, controlling costs and meeting consumer needs. Three important factors for effective component integration are outlined in the paper. These are the generation of a hierarchical model structure, representation of the system environment and knowledge of the impact of spatial and temporal factors on the system. A value chain model overlays the physical supply chain model. Product value is modelled and agent-based simulation of manager decisions are incorporated, forming a functional value chain model. A model was used to identify processes, material flows, information and financial flows. The model was customised or calibrated to mill areas and case studies were carried out. Results showed that the success of the model depends largely on the input from reference groups. Future plans are to implement dynamic inputs to replace the manual controls.

Another example of an integrated supply chain model is the Global Model developed by Loubser (2002) to assess the effect of delivered sugar on factory output. The model integrates existing models of harvesting and milling. Detailed modelling of individual components would require expertise and a significant investment of capital and time, hence the processes were significantly simplified. The model begins by calculating sugarcane properties (i.e. pol %, brix %, fibre %, ash % and water %) from historical mill records. Harvesting methods are represented by a purity factor, which is a function of burn or green harvest practice, trash levels and delay (converted into deterioration). Transport is represented by a delay factor and spillage losses, effectively representing a loss of pol %. Processing is represented as a single equation for target purity, which determines the maximum sugar recovery. The model is currently used for benchmarking and indicating trends, but not for predicting output, due to many over simplifications.

Determination of the optimum length of milling season (LOMS) is a complex task which seeks to balance the increase in profits from harvesting in the peak sucrose window, with increased equipment and infrastructure costs. Such an investigation requires consideration of the supply chain and is ultimately an economic exercise, balancing capital invested into capacity gains against economic returns. Hildebrand (1998) developed a model to optimise LOMS for a fixed mill capacity and varying sugarcane supply in the South African sugar industry. The model is based on LP principles and is formulated in an MS Excel spreadsheet. Three approaches are considered, namely to vary both sugarcane supply and milling capacity, or varying only one of these at a time. The approach of varying sugarcane supply for a fixed mill capacity was selected as the industry was experiencing an expanding sugarcane supply. The model considers the supply chain as a single business entity by ensuring a fixed division of proceeds between millers and growers. Beginning with the growing component, the CANEGRO simulation model is used to predict yield. Milling revenue is calculated by an estimated recoverable crystal formula and three driver costs are considered, namely seasonal, weekly crushing and throughput related costs. The model determines at what time marginal losses to growers and millers are matched by the benefits of mill utilisation. The model has been used as a guideline during negotiations to determine the LOMS. Mill capacity design was not considered in the model discussed above. It is complicated by seasonal sugarcane quality variation. Mills are usually designed to crush sugarcane of average quality, which results in bottlenecks in different components during the season (Hildebrand, 1998).

Nguyen and Prince (1995) developed a model to reduce the cost of ethanol production, which is more expensive than that of sugar in the Australian industry. The model optimises ethanol plant capacity by balancing transport costs, which increase with plant size, against production costs, which decrease due to economies of scale. The model uses algebraic equations to determine the unit cost per mass of sugarcane and integrates the unit cost over the transport distance. An algebraic equation representing total factory cost was derived to determine the optimum ratio of transport to production cost.

Environmental authorities are putting growers under increasing pressure to trash sugarcane. The choice between trashing and burning requires an integrated evaluation of impacts on grower, transport and milling components. Such a study was done by Cock *et al.* (2000) who developed a simple spreadsheet model to compare the profitability of different sugarcane treatments in the Columbian industry. Harvesting, transport and milling costs per ton are represented algebraically. The model facilitates assessing the impact of variety, burning and irrigation (which determine trash levels) on transport efficiency and sugarcane payment, and can easily be adapted for other crops. A similar model was developed by Wynne and van Antwerpen (2004) for the South African industry. They developed a spreadsheet based model to determine if trashing or burning is more economical within a given area. The model includes the full supply chain from field production through transport to raw sugar production. Production cost figures and deterioration rates (using the Loubser (2002) model) are used to calculate production costs and miller income. The model shows that there are areas where trashing is more economical. There is room for further development in areas such as cogeneration, which supports trashing.

Another simulation model representing the full sugar supply chain is the MAGI model developed by le Gal *et al.* (2003). The model was designed for the management of sugar supply from growing to mill crushing in La Réunion and it was later adapted to the South African industry. MAGI can be used to assist millers and growers to manage the supply chain through restructuring of mill areas, changing delivery allocation rules, the length of milling season and the division of different areas according to variations in sugarcane quality. The model structure is shown in Figure 3.5.

The model runs at a weekly time step and therefore does not consider machinery scheduling. This approach was seen to be more practical than an optimization approach as it would be impractical to find optimal solutions with such a high level of integration. Simulation also provides a basis for negotiations between millers and growers, serving as a decision support tool. The model was initially formulated in a spreadsheet and later converted into MS Access format.

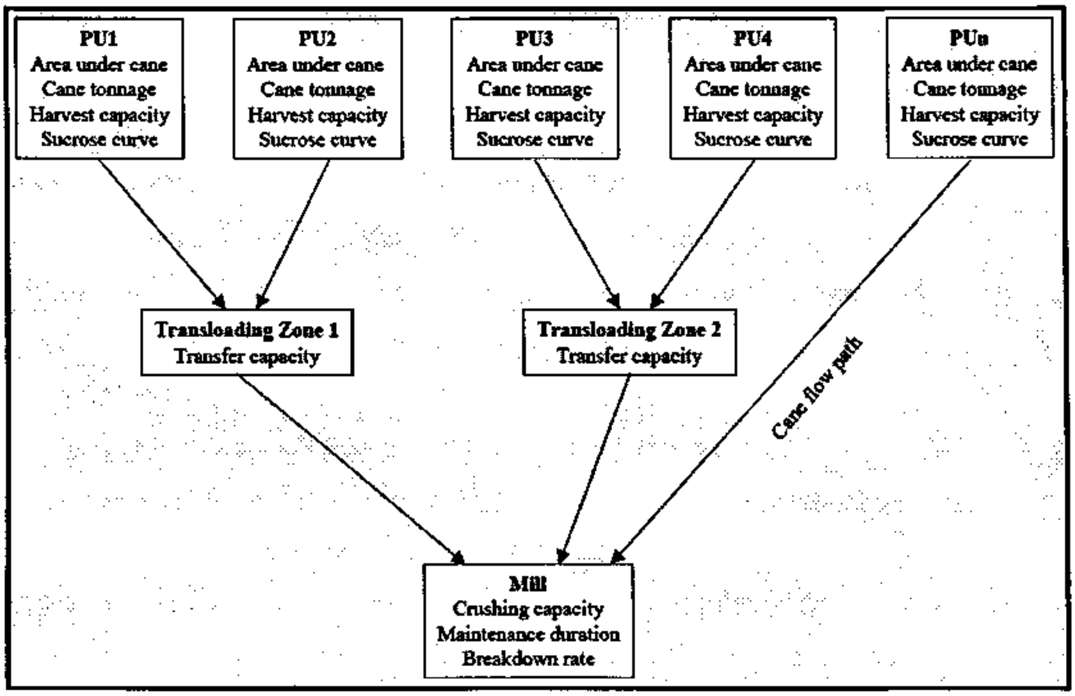

Figure 3.5 A MAGI representation of mill supply area structure (le Gal *et al.*, 2003)

Figure 3.5 shows how large farms or zones of similar sugarcane quality are represented by production units. Each unit is characterised by its area, yield, harvest and transport capacity and sucrose curve, which excludes the impact of harvesting procedures. The production unit data are mill based. As explained in Section 3.3.3 transport is a critical component as it involves high costs and the quantity and quality of the sugarcane delivered impacts the total sugar produced. The variables associated in this component are harvest, transport and mill capacities, delivery allocation rules and varying (spatially and temporally) sugarcane quality. Sugarcane is delivered from the production units via the relevant infrastructure to the mill. Each transport entity has a capacity. The mill capacity is calculated by multiplying the mill crush rate by weekly operating hours and a mill delay factor. Unforeseen delivery and mill delays can be input facilitating sensitivity analysis.

3.5 Conclusions

A range of models used in sugar supply chain planning have been reviewed. Generally, crop growth is simulated, harvest and transport are modelled using LP, IP or MIP and milling is simulated. Modelling techniques used for integrated supply chain problems ranged from simplified spreadsheets to complex simulation models.

There is a general opinion in international sugar industries that models of the full supply chain are required to investigate new avenues for production and efficiency improvements. Such models serve to evaluate the impact of factors which affect the full supply chain and ultimately determine best practices for the profitability of the supply chain as a single entity. The need for integrated management has been met with the development of various integrated supply chain models. Trends in the literature showed that crop growth is usually simulated, harvest and transport are modelled by linear, integer and mixed integer programming, and milling is most commonly simulated. Relatively simple integrated systems have been formulated into single models, while complex integrated models are run as series of separate models in parallel. It is believed that, in future, supply chain models will achieve higher technical integration. To date relatively simplified models have been used to address integrated planning problems in the South African sugar industry in comparison to those used in other sugar supply chain industries worldwide.

4 THE DEVELOPMENT OF A SUGAR SUPPLY CHAIN MODEL FRAMEWORK

4.1 Introduction

In Chapters 2 and 3 a range of models developed for agri-forest supply chains (SC) were discussed with a focus on the sugarcane SC. A detailed description of the sugarcane SC was included (Section 3.2), describing variable changes and their impacts on processes as sugarcane moves through each component.

The overall aim of this project was to develop and verify the suitability and feasibility of an integrated SC model for the South African sugar industry. Such a model should serve as a tool for representing SC processes and improving system efficiencies in the context of the SC as a single business entity.

Few integrated SC models for addressing planning problems in the sugarcane SC were found in the literature. Some simplified models have been developed for specific problems, such as optimising the length of milling season (Hildebrand, 1998). These models provide insight into useful modelling techniques and model input information. However, the operational principles of the CAPCONN model framework were developed from first principles, independent of the literature reviewed, and hence they have no connection to Chapters 2 and 3.

The main objective of this chapter is to present an integrated sugarcane SC model framework based on the pipe flow relationship between capacity and throughput. This operational principle is referred to as capacity constricted conveyance (CAPCONN). The development process is summarised in Figure 4.1. The overall conceptualisation, formulation and construction are firstly discussed (Sections 4.2, 4.3 and 4.4, respectively). Conceptualisation involved identifying the significant capacity driving variables and the operational principles. The operational principles refer to the theoretical approach of representing the physical system. Model framework formulation involved representing each SC component by the operational principles. Model construction refers to how the model was developed in an MS Excel spreadsheet and is discussed in Section 4.4. The means of data acquisition and system evaluation are dealt with in Chapters 5 and 6.

- Model framework conceptualisation
  - Significant variable identification (Section 4.2.1)
  - Definition of operational principles (Section 4.2.2)
- Model framework formulation
  - CAPCONN representation of each SC component (Section 4.3.3)
- Model framework construction
  - Software development of CAPCONN (Section 4.4)

Figure 4.1 CAPCONN development process

4.2 Model Framework Conceptualisation

The first step undertaken to develop the CAPCONN modelling concept is variable identification, which aims to identify the twenty percent of variables that control approximately eighty percent supply chain operations. The variables identified determine which of the processes described in Section 3.2 are included in CAPCONN. Thereafter, the fundamental operational principles of the model framework are proposed. This includes component capacity, process performance, quality and cost. Section 4.4 explains which components are included in the economics calculations.

4.2.1 Determination of significant variables

The integration of the SC from field to mill requires significant simplification, but also the inclusion of certain fundamental aspects. Although very important, the reason for excluding a growing component in CAPCONN is that the nature of the crop growth process is unique, and not easily included in an integrated model of mechanical operations. Crop growth would best be included as a sub-model running in parallel with an integrated model, as mentioned in Section 3.3. Similarly, beyond raw sugar production, supply chain operations would best be modelled by a value chain model, accounting for management decisions.

According to Higgins and Davies (2005) the optimisation of the full sugarcane harvest system using a mathematical model is an intractable task owing to the complexity of the various processes. It is therefore necessary to simplify the system to a level of complexity that can be sufficiently modelled, while maintaining a level of accuracy and representation of the actual system.

The variables identified in this section are those variables (termed driver variables) that were perceived to drive SC processes by regulating capacity and quality properties. Numerous other inputs are required to calculate coefficients and sugarcane composition, which are discussed in Section 4.2.2. A range of possible driver variables were sourced from the literature, through industry consultation and analysing the algorithms of previously developed models. Driver variables were selected according to their impact on sugarcane quality, SC capacity and process efficiency.

The driver variables used in CAPCONN are the sugarcane composition descriptive variables, namely sucrose, non-sucrose, fibre and ash (primarily soil) contents. These variables describe sugarcane quality and often regulate mill component throughput capacities. Mill separation efficiency is often a function of some of these sugarcane quality variables. The mass flow rate of sugarcane is also considered to be a driver variable.

Sucrose is the primary income generator for the sugar industry, hence process impacts on sucrose content and ultimately sugar recovery need to be considered. The throughput capacity of a mill is often regulated by high sucrose contents in the A-Pan, often during the midseason when sucrose levels naturally peak (Pillay, 2005).

Fibre was selected since it is often the regulator for preparation and extraction throughput capacity. It also reduces sucrose extraction efficiency (Kent *et al.*, 1999). Mill capacity is usually regulated by fibre levels during the early season (Pillay, 2005).

Non-sucrose is also an important regulator of mill component capacity, often during late season when high non-sucrose contents limit C-Pan throughput capacity (Pillay, 2005). Although non-sucrose contains many compounds, these are not easily disaggregated and it was therefore most suitable to view non-sucrose as a single variable.

Soil levels were included as they regulate mill operation through the potential to extinguish boiler fires and hence stop the mill (*pers. comm.*[5]). Soil levels have also been shown to significantly impact sugar recovery and mill maintenance costs (ESR, 2005).

As described above, the primary sugarcane composition variables were selected to estimate sugarcane quality and the effects on SC capacity. Figure 4.2 shows sugarcane flow through the SC viewed in terms of these primary sugarcane composition variables. From the field to mill gate sugarcane components remain combined while undergoing deterioration. The modelling of these components is discussed in Section 4.3.1. Deterioration includes sucrose deterioration, non-sucrose generation and mass loss. Once in the mill, separation occurs during the extraction process. Fibre and ash exit the SC as bagasse, while the remainder of the produce is transferred to the mixed juice tank. Sucrose and non-sucrose are the primary compounds transferred to the mill back end where they are separated by the A, B and C stations.

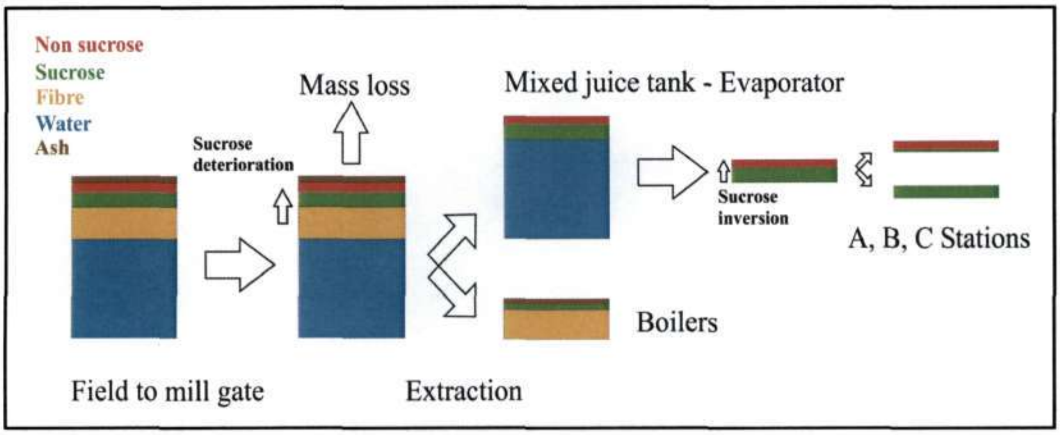

Figure 4.2 CAPCONN visualisation of sugarcane flow in terms of driver variables

4.2.2 CAPCONN operating principles

After identifying the significant variables in Section 4.2.1, it was necessary to determine how they would be interlinked when conceptualising the SC. The SC is viewed in terms of four fundamental concepts listed below:

- Component throughput capacity,

[5] S. Davis, Mill Process Engineer, SMRI, Durban, South Africa, January 2006

- Sugarcane quality,
- Mill process separation efficiency, and
- Cost

Sugarcane quality and process separation efficiency are indirectly related to throughput capacity as efficiencies determine the quality of produce exiting a process. Various mill process capacities are regulated by quality (*pers. comm.*[6]). The fourth concept is cost, which ultimately drives SC planning and management decisions.

A weekly time step was selected because comprehensive weekly mill performance reports were available from SMRI. This information can be used to determine relationships between processes and to serve as modelling inputs. A weekly time step simplifies the model framework, omits operational factors, such as scheduling, and allows the user to focus on strategic and tactical planning issues.

Sugarcane conveyance through the SC is limited by the throughput capacity of each component. For example, the transport component can only move sugarcane as fast as the number of trucks available allow, while the sugarcane shredder in the mill can only handle a specific quantity of fibre per hour. The SC can only process sugarcane at a capacity equal to or less than the single most constricting component. Fixed costs are considered to be constant throughout the season.

4.2.2.1 Symbol notation

For the purpose of simplicity, SC components and variables were represented by standardised symbols, shown in Tables 4.1 and 4.2.

The notation was used to represent components and variables individually, as well as variable values within each component. For example S_X represents the sucrose content after the exhaustion component and C_{SX} represents the weekly sucrose throughput capacity of the exhaustion component.

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[6] S. Davis, Mill Process Engineer, SMRI, Durban, South Africa, January 2006

Table 4.1 Notation for supply chain components

Component	Symbol
Harvest	H
Loading	L
Transport	T
Off loading	OL
Preparation	P
Extraction	E
Boiler	B
Exhaustion	X

Table 4.2 Notation for supply chain variables

Variable	Symbol	Unit
Sucrose	S	%
Non-sucrose	NS	%
Fibre	F	%
Ash	A	%
Tops	TS	%
Trash	TSH	%
Stalk	ST	%
Quality or compound % of total produce mass	α	%
Truck payload	ρ	tons
Weekly throughput capacity	C	$t.wk^{-1}$
SC constricting capacity	C_{min}	$t.wk^{-1}$
Throughput rate capacity	γ	$t.hr^{-1}$; $t.day^{-1}$
Operational throughput rate	y	$t.hr^{-1}$; $t.day^{-1}$
Capacity utilisation	CU	%
Effective hours operated	t	$hr.wk^{-1}$
Unavailable operational time	U	$hr.wk^{-1}$
Cost	π	R

4.2.2.2 Estimating component throughput capacity

Only those components likely to form bottlenecks were included in the capacity modelling component of CAPCONN. Field to mill capacities are solely a function of sugarcane mass and volume and all the components involved were included as possible bottlenecks. These are the harvesting, loading, transloading and transport components. Only the components that could be potential bottlenecks in the mill were included. These are preparation, extraction, the boilers and the A-Pan and C-Pan. Preparation and extraction are limited by fibre levels and boiler capacity is limited by soil levels. A-Pan and C-Pan capacities are limited by sucrose and non-sucrose contents, respectively.

CAPCONN represents each component's capacity in terms of weekly processing capacity *C*. In order to determine the weekly throughput capacity of a respective component, t and γ are multiplied as shown in Equation 4.1.

$$C_i = t_i \times \gamma_i \qquad (4.1)$$

where i can reflect any SC component as summarised in Table 4.1.

Within a one week time step t is considered to be a constant, referring to the actual time in the week that a component operated at its capacity. It does not represent the time that the component was available for use. Hence, operational efficiency and equipment utilisation are assumed to be 100%. If the operational efficiency was sub optimal, it must be accounted for by reducing either t or γ. The concepts of operational efficiency and equipment utilisation are of interest in operative (1 day to 6 months) and online (1 day) planning and are addressed by more specific models which include factors such as scheduling and buffer capacity. For visualisation purposes t and γ were set on the x and y axes as shown in Figure 4.3.

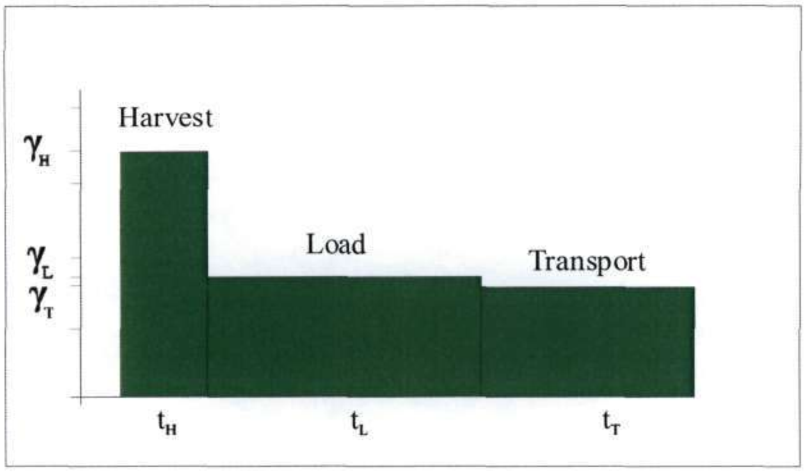


Figure 4.3 CAPCONN's capacity visualisation methodology

The surface area of each component equals C of that particular component. Since the various sugarcane plant compounds are separated in the mill it was necessary to convert the y_S, y_{NS}, y_F, y_A, γ_S, γ_{NS}, γ_F and γ_A to an effective $y_{sugarcane}$ and $\gamma_{sugarcane}$ respectively. Note $\gamma_{sugarcane}$ represents the smallest component $y_{sugarcane}$ in the SC.

4.2.2.3 CAPCONN's constrictor and utilisation principles

The flow through the SC is analogous to pipe flow. On a daily operational level, sugarcane flows are expected to vary between components but on a weekly time step y was assumed to be constant in all components. In CAPCONN the SC is considered to operate at a rate equal to C_{min}. C_{min} equals the minimum C of all the components in the SC as shown in Equation 4.2.

$$C_{min} = \min(C_1, C_2 \ldots C_i \ldots C_n) \tag{4.2}$$

A y greater than the y corresponding to C_{min} will create a bottleneck at the component with $C = C_{min}$. Figure 4.4 shows C and C_{min} plotted on the same axes with $C_H = C_{min}$. Since t was considered to be constant over time, γ is adjusted to y so that C in each component equals C_{min}.

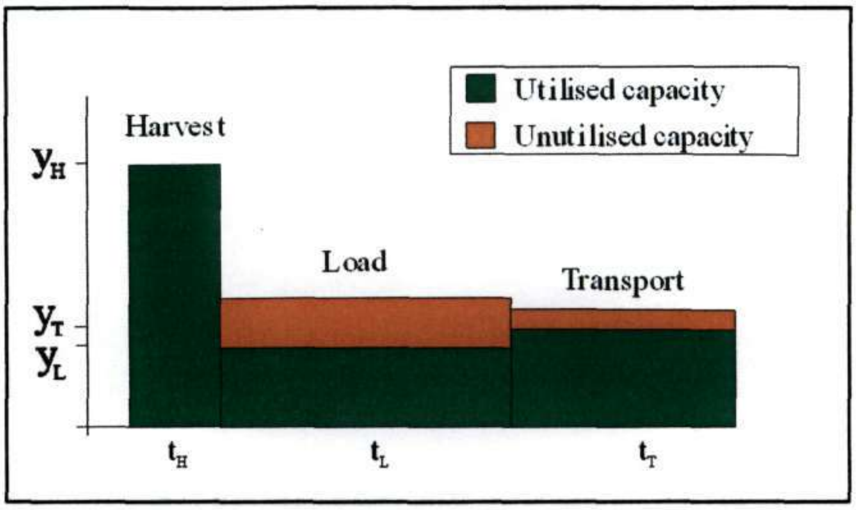


Figure 4.4 CAPCONN's utilisation visualisation methodology showing harvesting 100% utilised with a capacity equal to C_{min}

When using a weekly time step the feedback systems involved on an operative and online planning horizon are excluded. Significantly more detailed information on process cycle times are required in order to determine the impacts such as the delays in each component resulting from a bottleneck or mill stoppage.

Capacity utilisation (*CU*) indicates the percentage of available capacity used in each component when the SC is operating at C_{min}. The capacity utilisation of each component is calculated according to Equation 4.3.

$$CU_i = \frac{y_i}{\gamma_i} \tag{4.3}$$

4.3 Model Formulation

This section describes the process of applying the theoretical principles outlined above to each component of the SC. The modelling of sugarcane quality was firstly discussed followed by the modelling of deterioration and component operations.

4.3.1 Representing sugarcane quality and modelling deterioration in CAPCONN

CAPCONN models sugarcane quality through the use of a sugarcane composition table after Wynne and van Antwerpen (2004). The composition table represents pre-harvest composition, as illustrated in Table 4.3. Input values are displayed in italics. Inputs included the *TS* %, *TSH* % and *ST* % in the sugarcane, within which the proportion of sucrose, non-sucrose, fibre and ash is provided.

An additional row was included to calculate the mass proportions of the sugarcane supplied, shown in the last row of Table 4.3. This row calculated the changes in the total seasonal harvest mass, a constant model input, in each component from the field to the mill. The addition of soil, increases the sum of the % mass of sugarcane. Hence, the sum of the total sugarcane composition column may rise above 100%, showing the composition of sugarcane material is higher than the infield composition. The total mass may however be lower as a result of evaporation and other mass losses.

Table 4.3 An example of CAPCONN's sugarcane quality representation

Sugarcane composition before harvest	**Tops**	**Trash/Leaves**	**Stalk**	**Total**
% fresh mass	17.62%	6.95%	75.43%	100.00%
Sucrose	0.2%	0.0%	12.60%	9.5%
Non-sucrose	3.8%	1.0%	2.87%	2.90%
Fibre	16.0%	89.0%	11.40%	17.6%
Insoluble Ash	0.5%	0.5%	0.50%	0.5%
Moisture	79.5%	9.5%	72.6%	69.5%
Total	100.0%	100.0%	100.0%	100.0%
Mass (Mt.season^{-1})	0.49	0.19	2.11	2.80

The composition table facilitates integrated modelling as it links the sugarcane quality in each component to the quality in the following component. This is achieved by passing the quality to the following component after adjusting the quality values according to the operation and time delay incurred between the components. For example, if trash is increased, transport will be directly affected as truck payloads will contain a higher proportion of trash and hence less stalk. The mill will also receive less sugar per unit sugarcane mass as a lower proportion of the sugarcane processed is stalk.

Deterioration, in this report, refers to the natural processes of sucrose inversion to non-sucrose and sugarcane mass loss due to evaporation and respiration. All three processes have a dependence on the time delay from harvest and temperature.

Mass loss is modelled using a time based mass loss coefficient, according to Wynne and van Antwerpen (2004) shown in Equation 4.7. Mass loss is only considered up to the mill front end, thereafter the process was assumed to no longer occur.

$$ML = c_1 \times D \tag{4.7}$$

where:

ML = mass loss (%),

c_1 = daily mass loss (0.291% and 0.814% for green and burned whole stalk sugarcane respectively) and

D = delay from time of harvest (hr).

Sucrose loss up to the mill front end is modelled as a function of hourly delay and the ambient temperature in Kelvin after Wynne and van Antwerpen (2004), shown in Equation 4.8.1. The coefficient c_2 was assumed to be 2 for burned whole stalk and green billeted sugarcane (*pers. comm.*[7]). The sucrose loss is applied to the sucrose within the stalk, tops and trash. The non-sucrose formation is assumed to be proportional to the sucrose loss, hence non-sucrose levels are increased by the *SL*.

$$SL = c_2 \times (1 - EXP(-h) \times EXP(-(9498/(K) + 24.1))) \tag{4.8.1}$$

where:

SL = sucrose loss before the mill (%) and

K = temperature (K).

c_2 = 1 for green whole stalk sugarcane and 2 for burned whole stalk

[7] S. Davis, Mill Process Engineer, SMRI, Durban, South Africa, January 2006

and green billeted sugarcane and

h = delay since harvest (hr).

The term "inversion" is used to represent the loss of sucrose to non-sucrose in the mill. Since there is a negligible formation of viscous enhancing non-sucrose compounds in the mill, no adjustments were made to non-sucrose levels (*pers. comm.*[7]). This is because viscous enhancing non-sucrose compounds limit C_X. The Vucov equation is used by the SMRI to estimate inversion losses (*pers. comm.*[7]). Theoretical inversion loss percentages for each component are estimated from research or consultation. Inversion losses were calculated using Equation 4.8.2.

$$SL = c_3 \times S \tag{4.8.2}$$

where:

SL = sucrose loss in the mill (%),

c_3 = component sucrose loss (%) and

S = sucrose content (%).

4.3.2 Modelling different components of the supply chain

CAPCONN calculates three aspects of operational processes; (1) component capacity (γ), (2) component impacts on sugarcane quality and (3) operational performance. The value of γ of all components is based on data in scientific literature as well as consultation. The value of t for each component can be obtained through consultation with experts in the field.

Before the product enters the mill, component capacities are dependent on $\gamma_{sugarcane}$. Inside the mill, however, component capacities are functions of both throughput and sugarcane quality. Using data organised as in Table 4.3, γ of each mill component was converted to $\gamma_{sugarcane}$, allowing all component capacities to be inter-comparable (Equation 4.13).

$$\gamma_{sugarcane} = \gamma_i \div \alpha \tag{4.13}$$

where:

$y_{sugarcane}$ = mill component sugarcane throughput capacity ($t.hr^{-1}$),

y_i = mill component sugarcane compound throughput capacity ($t.hr^{-1}$) and

α = compound % of total produce mass.

Changes in α (i.e. *TS*, *TSH* and *ST*) were recorded in the sugarcane composition table described in Table 4.3. Table 4.4 shows the composition table transferred between components from harvesting to offloading. Three additional data points were added to components between harvest and the mill front end, to account for deterioration effects and changes in ash levels. Changes in ash levels were applied to the ash levels within the stalk, tops and trash columns. Constant stalk, tops and trash mass ratios were used, hence sugarcane mass varied proportionally to change in ash levels. Table 4.4 shows a sample of these data, in this case for the point after cane is loaded for transport.

Table 4.4 Sugarcane compositions assumed after the loading stage for burned sugarcane

	Total	**Tops**	**Trash/Leaves**	**Stalk**
% fresh mass	100.0%	0.0%	4.0%	96.0%
Sucrose	10.7%	0.2%	0.0%	11.2%
Non-sucrose	2.7%	3.8%	1.0%	2.8%
Fibre	16.0%	16.0%	89.0%	13.0%
Insol Ash	2.5%	0.5%	0.5%	0.5%
Moisture	70.0%	79.5%	9.5%	72.5%
Total	102.0%	100.0%	100.0%	100.0%
Mass component (Mt / season)	2.13	0	0.0845	2.03
Sucrose loss, non-sucrose increase (%)	0.03%			
Mass loss (%)	0.03%			
Ash percentage increase (%)	2.0%			

4.3.2.1 Harvesting (H)

The value of γ_H was calculated from the number of harvest units (*HU*) and y_{unit}, shown in Equation 4.14. Harvest units refer to the number of cutters and are in units of men or mechanical harvesters.

$$\gamma_H = HU \times y_{unit} \tag{4.14}$$

where:

γ_H = harvest capacity (t.day^{-1}),
HU = number of harvest units and
y_{unit} = unit harvest rate (t.day^{-1}.unit^{-1}).

The *HU* was calculated from the seasonal sugarcane crush mass (*SM*), the length of milling season (*LOMS*) and harvest γ_{unit}. Equation 4.15 was used for manual and mechanical harvesting.

$$HU = (SM \div LOMS) \div y_{unit} \tag{4.15}$$

where:

SM = seasonal crush mass (tons),
LOMS = length of milling season (days) and
y_{unit} = unit harvest rate (t.day^{-1}.unit^{-1}).

4.3.2.2 Loading and transloading (L)

The value of γ_L was calculated using Equation 4.16. The number of loading units (*LU*) is determined through industry consultation. The value of loader γ_{unit} is determined from literature or consultation. This method applies to both field and zone transloading.

$$\gamma_L = LU \times y_{unit} \tag{4.16}$$

where:

LU = number of loading units and

y_{unit} = unit load rate ($t.hr^{-1}$).

4.3.2.3 Extraction and road transport (T)

Similar to loading, γ_T was calculated by multiplying the actual number of transport units (*TU*), obtained through consultation, by the vehicle y_{unit}. Vehicle y_{unit} was calculated from payload (ρ) and vehicle turnaround time (φ) (hr), shown in Equation 4.18. The value of φ was calculated using Equation 4.19, the input values were obtained from industry consultation. The delay times are weekly averages which are obtained from measured industry data.

$$\gamma_T = TU \times y_{unit} \tag{4.17}$$

where:

$$y_{unit} = \rho \div \varphi \tag{4.18}$$

where:

$$\varphi = d_1 + d_2 + d_3 + d_4 + d_5 \tag{4.19}$$

where:

d_1 = field queue time (hr),
d_2 = field load time (hr),
d_3 = inbound travel time (hr),
d_4 = outbound travel time (hr),
d_5 = offload, cleaning and shift change time (hr),
ρ = payload (tons) and
φ = turnaround time (hr).

4.3.2.4 Offloading (OL)

The value of γ_{OL} indicates the offloading capacity at the mill yard and is obtained from consultation with mill engineers. This value considers offloading directly onto the spiller tables, onto mill stockpiles or a combination of the two, depending on the mill.

4.3.2.5 Preparation (P)

The value of preparation throughput capacity (γ_P) was estimated solely as a function of *F*. The seasonal γ_{Pmax} and γ_{Pmin} were plotted against the seasonal range of fibre content,

α_{Fmax} and α_{Fmin}, as shown in Equation 4.20. All values are obtained through consultation with mill engineers.

$$\gamma_P = \gamma_{max} - (F_{max} - F) \times \frac{(\gamma_{max} - \gamma_{min})}{(F_{max} - F_{min})} \tag{4.20}$$

where:

γ_P = preparation throughput capacity ($t.hr^{-1}$),

F_{max} = maximum seasonal α_F (%),

F_{min} = minimum seasonal α_F (%),

F = actual fibre content α_F (%),

γ_{Pmax} = maximum seasonal γ ($t.hr^{-1}$) and

γ_{Pmin} = minimum seasonal y ($t.hr^{-1}$).

4.3.2.6 Extraction (E)

The value of γ_E was represented by the dewatering mill fibre handling capacity. This value was obtained through consultation with mill engineers.

CAPCONN models extraction efficiency (α_E) as a function of *F* and *A* levels, where F is largely determined by the amount of trash. These two parameters were selected after Meyer (1999) who outlined that the two most significant impacts on the mill when changing to mechanical harvesting were increased soil and trash levels. This subject is well researched. Kent *et al.* (1999) undertook an extensive literature survey into the subject and concluded an average increase in α_E of 0.4 units for a 5% decrease in trash. Such relationships are not useful when deriving an α_E function since they do not apply to a wide range of soil and trash level combinations.

The CAPCONN α_E function was derived by determining the average range of α_E over the season from mill records and industry consultation. Cárdenas and Diez (1993) showed that a 1% increase in soil and trash contents decreased α_E by 0.91% and 0.37% respectively. A two dimensional range for α_E (i.e α_E is a function of two variables) for a specific mill was used, according to the 0.91% and 0.37% proportions, shown in Equation 4.21. Soil and trash levels controlled 60% and 40% of the extraction range respectively. A_{max} and A_{min} (ash was assumed to be primarily composed of soil) were linearly correlated to 60% of the measured industry extraction range. The maximum and minimum trash levels were correlated linearly against 40% of the measured industry extraction range. Ranges of soil and trash were obtained from literature or consultation. In this way, α_E was formulated into a function of soil and trash while remaining within the measured industry maximum to minimum range. The calculated loss resulting from fibre and soil was then subtracted from the maximum α_E level, shown in Equation 4.21.

$$\alpha_E = E_{max} - c_4(A_{max} - A)\frac{(E_{max} - E_{min})}{(A_{max} - A_{min})} - c_5(F_{max} - F)\frac{(E_{max} - E_{min})}{(F_{max} - F_{min})} \tag{4.21}$$

where:

α_E = extraction efficiency (%),
E_{max} = maximum seasonal α_E (%),
E_{min} = minimum seasonal α_E (%),
F_{max} = maximum seasonal α_F (%),
F_{min} = minimum seasonal α_F (%),
F = actual α_F (%),
A_{max} = maximum seasonal α_A (%),
A = actual α_A (%),
A_{min} = minimum seasonal α_A (%),
c_4 = proportion of α_E loss due to soil (60%) and
c_5 = proportion of α_E loss due to trash (40%).

4.3.2.7 Boiler (B)

The next throughput capacity regulator in the SC is the boiler station. The boiler capacity (γ_B) is obtained through consultation with mill engineers. In CAPCONN the diffuser transfers 100% of the soil entering the mill to the furnace, based on the assumption that the mill recycles the clarifier mud. This is based on the observation that 10% of soil which typically enters the mixed juice tank returns to the diffuser when the mud is recycled (Pillay, 2005).

4.3.2.8 Exhaustion (X)

Constant values for γ_S and γ_{NS} in the A-Pan and in the C-Pan were assumed. These values are mill specific and obtained through consultation with mill engineers.

CAPCONN estimates exhaustion efficiency (α_X) in the A, B and C stations as a function of NS, shown in Equation 4.22. X_{max} and X_{min} were plotted linearly against NS_{max} and NS_{min}, which were obtained from literature or consultation. This function does not consider soil and trash impacts on α_X, only NS impacts. This may need to be taken into account when analysing exhaustion as soil and trash considerably reduce purity and therefore exhaustion (Cárdenas and Diez, 1993).

$$\alpha_X = X_{max} - (NS_{max} - NS)\frac{(X_{max} - X_{min})}{(NS_{max} - NS_{min})} \tag{4.22}$$

where:

α_X = exhaustion efficiency (%),
X_{max} = maximum seasonal α_X (%),
X_{min} = minimum seasonal α_X (%),
NS_{max} = maximum seasonal NS (%),
NS_{min} = minimum seasonal NS (%) and
NS = actual NS (%).

4.3.3 Modelling economics in CAPCONN

CAPCONN calculates the weekly cost of operating the supply chain by summing the costs of each component. Each component cost is split up into its component fixed cost (FC) and variable cost (VC), and a stock cost (STC) is also assigned to each component. A total of 15 components were included in the economic assessment, shown in Table 4.5.

Table 4.5 Supply chain components included in the economic assessment

Field to mill	Mill front end	Mill back end
Harvest	Preparation	Heating
Load	Extraction	Clarification
Transload	Boiling	Evaporation
Transport		A-Pan
		A-Crystaliser
		C-Pan
		C-Crystaliser
		Centrifuges

The total production cost (TC) is calculated by summing the total cost of each component, shown in Equation 4.9.

$$TC = \sum_{i=1}^{n} FC_i + VC_i + STC_i \tag{4.9}$$

where:

TC = total production cost of supply chain ($R.wk^{-1}$),

FC_i = fixed cost of component i ($R.wk^{-1}$),

VC_i = variable cost of component i ($R.wk^{-1}$) and

STC_i = stock cost of component i ($R.wk^{-1}$).

The *FC* is represented by $R.wk^{-1}.unit^{-1}$ of capital. The *VC* is represented by $R.t^{-1}$ of sugarcane for each component. Prior to the mill, the *VC* is in $R.t^{-1}$ of sugarcane while in the mill, costs are represented by $R.t^{-1}$ of fibre, ash or sucrose, depending on the particular component. The only *VC* that is not given on a "per ton" basis is the cost of milling soil, which was represented by a single combined value accounting for *VC* in all front end components. Variable costs are calculated by multiplying the SC throughput rate C_{min} by the $R.t^{-1}$ per unit sugarcane or sugarcane compound, shown in Equation 4.10.

$$VC = C_{\min} \times vc \times \beta \tag{4.10}$$

where:

VC = variable cost ($R.wk^{-1}$),

vc = component throughput cost of sugarcane compound ($R.t^{-1}$),

β = sugarcane compound percentage mass of total sugarcane mass (%) and

C_{min} = minimum C of all supply chain components.

The *STC* represented the opportunity cost associated with the time and value of sugarcane at each position in the SC. As sugarcane travels through the SC the *STC* value compounds. The *STC*, in units of $R.wk^{-1}$, was calculated from growing through to the mill back end, hence an additional agronomic *VC* was required. The equation used to calculate the *STC* per component cycle is shown in Equation 4.11 below. The *OC* rate represents the rate at which financial loss occurs as a result of funds lying idle in stock.

$$STC = R \times C_{min} \times V \times OC = MP \times V \times OC \quad (4.11)$$

where:

STC = stock cost ($R.\ week^{-1}$),

R = produce residence time in component (weeks),

C_{min} = minimum C of all supply chain components ($t.wk^{-1}$),

V = product value ($R.t^{-1}$),

OC = the opportunity cost ($\%.wk^{-1}$) and

MP = mass of produce resident in component at any given time (tons).

The dual price (*DP*) is the required input cost to increase or decrease the throughput capacity of a SC component, or a series of components. This cost is not used in CAPCONN as it is only useful for optimisation purposes, however it was included in this chapter as it would be useful were CAPCONN to be developed into a model with optimisation capabilities. The DP was calculated by Equation 4.12.

$$DP = TC \div y \quad (4.12)$$

where:

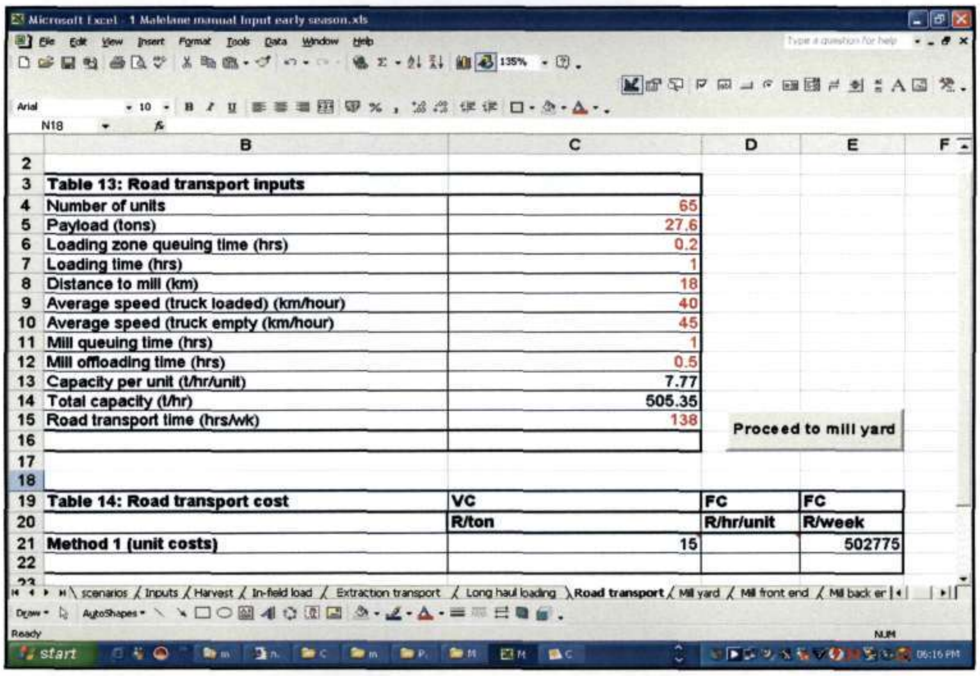
DP = seasonal dual price per component (R),

TC = seasonal cost per component unit (e.g. harvester, truck) (R.unit^{-1}) and

y = operational throughput rate (t.hr^{-1}).

4.4 Model Construction in MS Excel

CAPCONN was developed in MS Excel as series of worksheets, within a single file. User-friendly entry sheets capture general and operational inputs. A calculation sheet reads the capacities from all the input sheets. The C of each component is calculated as well as C_{min}. A diagnostics sheet calculates and displays capacity utilisation (CU), fixed cost (FC), variable cost (VC), stock cost (STC) and total cost (TC) are calculated. Figure 4.5 shows the transport component entry worksheet and Figure 4.6 shows the entry worksheet for the mill front end components. Figure 4.7 shows the calculation worksheet which determines the minimum component capacity. Only the sucrose calculation sheet is shown. Specialist understanding may be required to run this version of CAPCONN since some of the modelling concepts differ from mill to mill. For example, modelling a mill that uses a stockpile system would require an adaptation of the current Komati Mill modelling setup, which has not stockpile component.



	B	C	D	E
3	Table 13: Road transport inputs			
4	Number of units	65		
5	Payload (tons)	27.6		
6	Loading zone queuing time (hrs)	0.2		
7	Loading time (hrs)	1		
8	Distance to mill (km)	18		
9	Average speed (truck loaded) (km/hour)	40		
10	Average speed (truck empty (km/hour)	45		
11	Mill queuing time (hrs)	1		
12	Mill offloading time (hrs)	0.5		
13	Capacity per unit (t/hr/unit)	7.77		
14	Total capacity (t/hr)	505.35		
15	Road transport time (hrs/wk)	138	Proceed to mill yard	
19	Table 14: Road transport cost	VC	FC	FC
20		R/ton	R/hr/unit	R/week
21	Method 1 (unit costs)	15		502775

Figure 4.5 An example of CAPCONN's transport component worksheet which calculates fleet capacity and costing

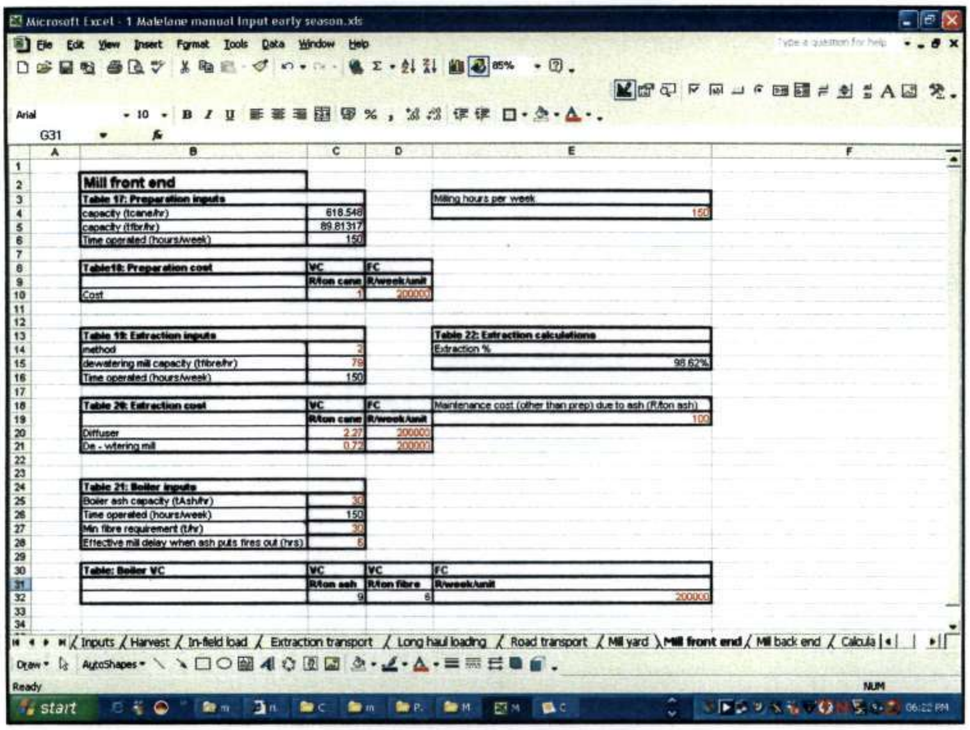


Figure 4.6 An example of CAPCONN's mill front end worksheet which calculates component capacity and costing

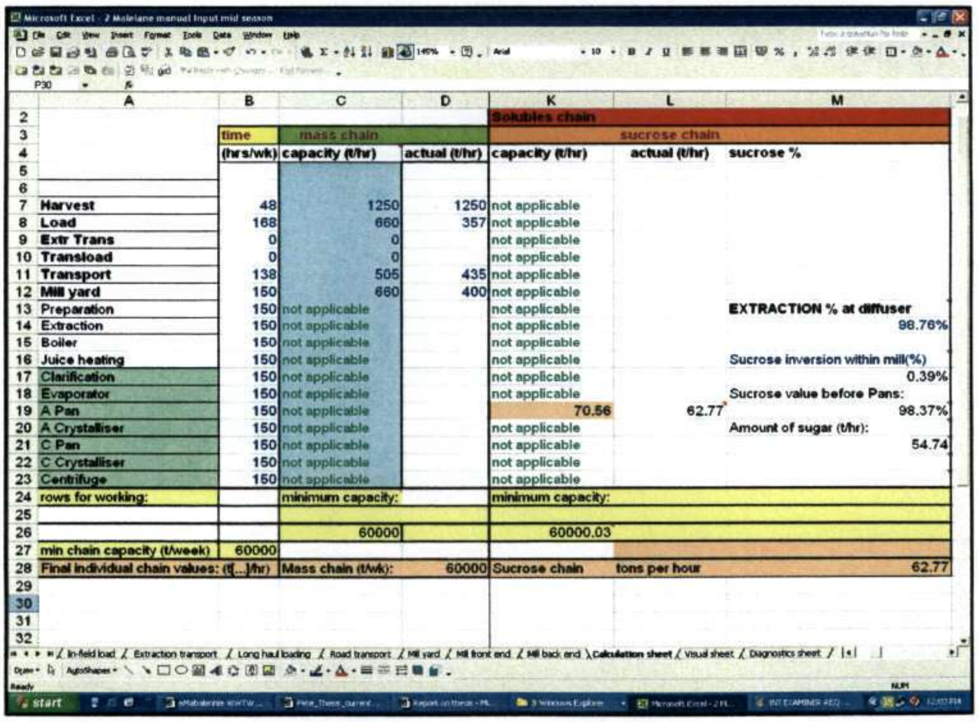


Figure 4.7 An example of CAPCONN's calculation worksheet which determines the minimum component capacity

5 A SUPPLY CHAIN CASE STUDY: MECHANISATION AT KOMATI MILL; METHODOLOGY AND MODEL INPUTS

5.1 Introduction

Chapter four describes the development of the CAPCONN sugarcane supply chain model framework. This chapter describes a mechanisation case study at Komati Mill, located in Mpumalanga, South Africa. The case study serves as an evaluation scenario for CAPCONN. As a result of a significant reduction in labour availability and performance for harvesting, and pressure to harvest green cane, contractors have begun to investigate the feasibility of implementing mechanical harvesting in the area. Mechanically harvesting sugarcane has a significant operational and financial impact on the supply chain, and the objectives of the case study were to quantify the effects on supply chain capacity and ultimately production costs. CAPCONN could also be used to identify problem areas and determine the feasibility of adjusting component capacity and performance.

It should be noted that the mill component algorithms described in Chapter 4 have been developed specifically for a mechanisation case study, focussing on the impacts of soil and trash on the mill as explained in Section 4.3.3. Chapter 6 discusses the evaluation of CAPCONN and Chapter 7 discusses the case study results.

5.2 Scenarios

Twelve scenarios were simulated at Komati Mill to compare the integrated SC impacts of manual and mechanical harvesting. The scenarios were (1) manually harvested burnt, (2) manually harvested green and (3) mechanically harvested green sugarcane in the early, mid and late season (3×3=9 runs). In addition, a wet scenario in the late season was also considered for all three harvesting scenarios (3 additional runs). The wet season was assumed to have higher trash and soil levels that enter the mill. Manually harvested burnt and green sugarcane are termed Scenario 1 and 2, respectively and mechanically harvested green sugarcane is termed Scenario 3. The Komati Mill area currently practices Scenario 1 to the largest extent.

5.3 CAPCONN Configuration for Komati Mill

Modelling inputs were obtained from literature and consultation with members involved in the harvesting, transport and milling SC components. Where necessary, inputs were sourced from research done in other mill areas worldwide. This section describes the modelling inputs used for this case study. These include sugarcane quality inputs and general and operational modelling inputs.

5.3.1 Cane quality

Since sugarcane quality varies over the course of the season, inputs to the model for sugarcane composition were varied for the early, mid and late season scenarios. Average sucrose (*S*), fibre (*F*) and non-sucrose (*NS*) levels were obtained from Komati Mill staff and assumed to be representative of sugarcane delivered to the mill (*pers. comm.*[8]). The values are shown in Table 5.1.

Table 5.1 Average pre-milling sugarcane composition in the early, mid and late season at Komati Mill (% of total sugarcane mass) (*pers. comm.*[9])

	Early season (April to June)	**Mid season** (July to September)	**Late season** (October to December)
Sucrose (%)	11.0	16.0	12.0
Fibre (%)	14.5	12.5	14.5
Non-sucrose (%)	2.8	2.6	2.8
Insoluble ash (%)	1.5	1.5	1.5

While the data in Table 5.1 are for sugarcane quality in the mill yard, inputs for CAPCONN need to be for conditions at the time of harvest. Therefore a back calculation had to be made to obtain the sugarcane quality at the time of harvest. This was achieved by manually adjusting the sucrose and non-sucrose values in Table 4.3, Scenario 1, till the same sugarcane quality parameters as shown in Table 5.1 were achieved. Values for tops (*TS*), trash (*TSH*) and stalk (*ST*) were taken from Table 4.3 and the tops and trash composition in Table 5.2 was assumed. These inputs were

[8] A. Williamson, Mill Manager, Komati Mill, Komatipoort, South Africa, March 2006

obtained from the Trashing Model (*pers. comm.*[9]) and were assumed to remain constant throughout the season.

Table 5.2 Assumed levels of tops and trash (*pers. comm.*[10])

	Tops %	Trash %
Sucrose (%)	0.2%	0.0%
Fibre (%)	16.0%	89.0%
Non-sucrose (%)	3.8%	1.0%
Insoluble ash (%)	0.5%	0.5%

5.3.2 General inputs

A number of general model inputs are described in Chapter 4, the values of which are discussed below. The option of harvesting burnt or green sugarcane indicates which deterioration equation to use, which was explained in Section 4.3.1.2. Estimated mean ambient temperatures for the early (April), mid (July) and late (October) seasons were assumed to be 14°C, 10°C and 16°C, respectively. A HTCD of 45 hours and 33 hours were used for burnt and green manual harvesting respectively (*pers. comm.*[10]). The HTCD for mechanical harvesting was assumed to be 3 hours (*pers. comm.*[11]). A daily mass loss of 0.291% was assumed for green whole stalk sugarcane and 0.814% for burnt whole stalk and green billets. These coefficients were obtained from the Trashing Model (*pers. comm.*[12]).

Agronomic variable costs (VC) of 18 $R.t^{-1}$ and 22 $R.t^{-1}$ for green and burnt sugarcane, respectively, were obtained from the Trashing Model. A seasonal infield sugarcane mass of 2.8 million tons was used. Under the current harvest and transport methods, this reduced to 2.09 million tons of milled sugarcane, which corresponds to the 2005 Komati season tonnage (Anon, 2005). The difference between the two tonnages represents losses from topping, trashing, transport and deterioration. A theoretical opportunity cost of 20% was assumed.

[9] A. Wynne, Agricultural Economist, Canegrowers, Mt Edgecombe, Durban, South Africa, February 2006
[10] L. van Staden, Harvest contractor, Komatipoort, Mpumalanga, South Africa, March 2006
[11] S. Krieg, Procurement Manager, Komati Mill, Komatipoort, Mpumalanga, South Africa, March 2006
[12] S. Davis, Mill Process Engineer, SMRI, Durban, South Africa, January 2006

5.3.3 Operational inputs

This section describes the inputs for determining operational impacts on harvested sugarcane quality and the inputs for capacity calculations. Harvested sugarcane quality inputs for each component of the supply chain are firstly discussed, followed by a description of the capacity determination of each component. The inputs required for extraction (E) and exhaustion (X) are then discussed.

Impacts on harvested sugarcane quality, in each component, were simulated by adjusting the values of the sugarcane composition table (Tables 4.3 and 4.5) from one component to the next. After harvest, tops (*TS*) and trash (*TSH*) were combined in the trash (*TSH*) column. This is considered to be a reasonable assumption as most of the literature reviewed used a combined tops and trash value (e.g. Kent *et al.*, 1999).

5.3.3.1 Harvesting impacts on sugarcane quality

de Beer *et al.* (1989) measured a mass fraction of 0.5% tops (*TS*) and 2.7% trash (*TSH*) for manually cut and burnt sugarcane and 2.8 % *TS* and 6.9 % *TSH* for manually cut green sugarcane. The combined tops and trash were assumed to be 4% and 10% for manually cut burnt and green sugarcane, respectively. According to Meyer (1999), 5-20% of tops and trash are removed in green sugarcane mechanical harvesting. Meyer (1999) describes a study in which tops and trash of mechanically harvested green sugarcane were found to range between 7.4% and 10.6%. Tops plus trash were therefore assumed to be 8% for mechanically harvested green sugarcane.

Wet weather causes a significant increase in soil and trash levels in sugarcane (ESR, 2005). For the wet period scenarios, manually harvested burnt sugarcane, *TS* + *TSH* was increased from 4% to 6%, an assumption based on literature by Rein (2005). The value of *TS* + *TSH* for manually harvested green sugarcane was increased from 10% to 14%, after Rein (2005). Tops and trash levels of mechanically harvested green sugarcane were increased from 8% to 12% as moisture reduces the effectiveness of the trash removal system. This is a relatively conservative assumption compared to the 5% to 20% range stated by Meyer (1999).

Manual harvesting was assumed to have no impact on soil content. Mechanical harvesting impacts on soil levels were based on research by ESR (2005). Values of 8% and 30% inorganic solids were reported for best case and wet scenarios, respectively. CAPCONN assumes A_H to be 10% and 15% for dry and wet periods, respectively, as more soil is retained in the harvested sugarcane in wet conditions. Table 5.3 provides a summary of the inputs used.

Table 5.3 Summary of inputs for the harvesting component

Harvest method	**Manual**	**Manual**	**Mechanical**
Harvest treatment	**Burn**	**Green**	**Green**
Tops and trash (%) (Dry weather)	4	10	8
Tops and trash (%) (Wet weather)	6	14	12
Ash content change (%) (Dry weather)	0	0	10
Ash content change (%) (Wet weather)	0	0	15

5.3.3.2 Loading, offloading and mill yard impacts on harvested sugarcane quality

Mechanical loading is practiced in the Komati Mill area, in the form of non-slewing and excavator type slewing loaders. A 2% and 6% increase in A_L was assumed for manually harvested burnt and green sugarcane in dry and wet weather, respectively. These values were obtained from Neethling (1982) who found A_L to be 1.7% and 6% for Bell loaders in dry and wet weather, respectively. Table 5.4 provides a summary of the inputs used.

Table 5.4 Summary of inputs for the loading component

Harvest method	**Manual**	**Manual**	**Mechanical**
Harvest treatment	**Burn**	**Green**	**Green**
Ash content change (%) (Dry weather)	2	2	0
Ash content change (%) (Wet weather)	6	6	0

Komati Mill has a rock and trash removal system prior to preparation, the performance of which is unknown. Percentages of soil and trash removal were assumed by the author, based on the amount of soil and trash present and weather conditions. Table 5.5 shows the values used. The general trends in all scenarios were that (1) higher soil and trash levels will have an associated higher removal rate and (2) that less soil and trash are removed in wet weather.

Table 5.5 Soil and trash reduction values for the rock and trash removal system

	Harvest method and treatment	Soil % decrease	Trash % decrease
Dry weather	Manual burn	1.2	2.0
	Manual green	1.2	4.0
	Mechanical green	4.0	4.0
Wet weather	Manual burn	1.0	1.0
	Manual green	1.0	2.0
	Mechanical green	3.0	2.0

5.3.3.3 Harvest capacity determination

In order to compare scenarios effectively, mechanical harvesting capacity was calculated first and the number of labourers was then calculated according to the number of harvesters.

The number of mechanical harvesters required was determined using Equations 4.14 and 4.15. A value of 50 $t.hr^{-1}$ for y_{unit} was assumed for mechanical green sugarcane harvesting (*pers. comm.*[13]). A 24 hour harvest time, over a 7 day cycle for the full 38 week season was assumed. Downtime for repairs, shift changes and bad weather was assumed to be 40% per harvester. The seasonal crush mass was increased by 7% from 2.1 to 2.25 million tons to account for an estimated 7% loss of millable stalk (de Beer and Boevey, 1997). de Beer and Boevey (1997) showed that chopper harvester losses range from 6.8% to 15%. The lower value was assumed after de Beer and Purchase (1999), who measured losses ranging between 5% and 10%. This was assumed to be a result of improved technology.

Manual harvesting capacities were determined using Equations 4.14 and 4.15. At Malelane mill, neighbouring Komati Mill, a 9.2 $t.day^{-1}$ y_{unit} was considered to be a good harvest rate and 6.4 $t.day^{-1}$ y_{unit} an average harvest rate (*pers. comm.*[13]). Rounding off, 6

[13] L van Staden, Harvest contractor, Komatipoort, Mpumalanga, South Africa, March 2006

t.day^{-1} was used as the average unit capacity for burnt whole stalk sugarcane. de Beer and Boevey (1997) showed that manual harvesting incurs a 2.1% loss of millable sugarcane. This loss was not added to SM as the harvest rate of 6 t.day^{-1} was assumed to be a significant simplification in itself. Adding 2.1% to the harvest throughput would not improve the accuracy of representation of the system. The calculation of the number of manual harvesters began with matching the exact rate of 60000 t.wk^{-1}cut by the mechanical harvesting system. It was assumed that cutting takes place for 7 hours a day, 7 days a week and that the cutter rate is 6 t.day^{-1}.

The same method was used to determine the number of harvesters required for green sugarcane harvesting. de Beer *et al.*, (1989) and Meyer and Fenwick (2003) showed that y_{unit} was reduced by between 20% and 30% when harvesting green sugarcane. A 30% reduction in capacity was applied to the y_{unit} used for burnt sugarcane harvesting. Table 5.6 provides a summary of the inputs used.

Table 5.6 Summary of calculated harvesting capacities

Harvest method	Number of harvest units	Unit capacity (t.hr^{-1}.unit^{-1})
Mechanical harvesting	12	50
Manual harvest of burned sugarcane	1429	0.87
Manual harvest of green sugarcane	2144	0.58

5.3.3.4 Loading capacity determination

Loading inputs are only used for manually harvested sugarcane because mechanical harvesters automatically load sugarcane as part of their harvesting operation. Values were obtained through consultation with Komati Mill supply management. Currently there are 25 machines of which 16 are non-slewing and 9 are excavator type slewing loaders. It was assumed that 1 excavator performed the equivalent work of 1.5 Bell loaders. Hence, there were effectively 30 Bell loaders (16 + 9 × 1.5). A load capacity of 22 t.hr^{-1}.unit^{-1} was obtained from the Trashing Model. According to de Beer *et al.* (1989), this rate decreases by 23% when loading green harvested sugarcane as a result of the density decrease of green sugarcane. Hence a 20% reduction in capacity was used. At Komati Mill loaders are available to operate 24 hours a day, 7 days a week with an estimated utilisation time of 30% (*pers. comm.*[14]). Table 5.7 provides a summary of the inputs used.

Table 5.7 Summary of calculated loading capacities

Harvest method and treatment	Number of loading units	Unit capacity ($t.hr^{-1}.unit^{-1}$)
Manual harvest of burned sugarcane	16	22
Manual harvest of green sugarcane	16	17.6

5.3.3.5 Transport capacity determination

Transport inputs were obtained through consultation. There were an estimated 65 units of which 65% were trucks and 35% tractor-trailer units. The use of different loading and transport equipment necessitated additional cohorts (as outlined in the recommendations for future research). Cohorts refer to zones of similar sugarcane quality. For manual cut and burnt sugarcane, trucks were assigned a payload of 29 tons and tractor-trailer units 25 tons hence a mean ρ_{unit} of 27.6 tons ($0.65 \times 29 + 0.35 \times 25$) was used. For green whole stalk sugarcane payload was decreased by 25%. According to de Beer *et al.* (1989) a 44% payload reduction occurs under no topping, while a 25% reduction occurs with green topped sugarcane, as a result of the density decrease. Payloads increase in the case of mechanical harvesting, resulting from a higher density associated with billets. Olwage (2000) showed a 6 ton increase in payload with billeted sugarcane at Komati Mill, hence the existing 27.6 ton payload was increased by 6 tons. Transport units operate 24 hours a day, 7 days a week with an estimated 18% downtime (*pers. comm.*[15]). Hence t_T equals 138 hours / week ($7 \times 24 \times 0.82$). Table 5.8 provides a summary of the inputs used.

Table 5.8 Summary of calculated transport capacities

Harvest method	Number of units	Payload (tons)
Manual harvesting burned sugarcane	65	27.6
Manual harvesting green sugarcane	65	20.7
Mechanical harvesting green sugarcane	65	32.6

[14] S. Krieg, Procurement Manager, Komati Mill, Mpumalange, South Africa, March 2006
[15] R. Venter, Procurement Manager, Malelane Mill, Mpumalange, South Africa, March 2006

5.3.3.6 Offloading capacity determination

Offloading capacity was based on the maximum offloading rate at the mill. For a minimum offloading time of 5 minutes per truck, 12 loads could be offloaded on each of the two offloading lines, generating an offload capacity of 660 $t.hr^{-1}$ (2 × (12 × 27.6) tons). The capacity was increased by 18% to 780 $t.hr^{-1}$ for billeted sugarcane based on the 6 ton increase in payload explained in section 5.3.3.5. Offloading was assumed to occur whenever the mill was functioning.

5.3.3.7 Mill component capacity determination

Preparation capacity was modelled using Equation 4.20. The fibre (*F*) range was assumed to be 10% to 16%. These values were obtained from tops (*TS*) and trash (*TSH*) values of 7% and 3% in Table 4.3, after Kent *et al.* (1999). These levels were used in the sugarcane composition table to obtain the corresponding *F* levels. For billeted sugarcane the throughput range at Komati Mill was estimated to be between 550 to 630 $t.hr^{-1}$, while for whole stalk sugarcane a range of 460 to 520 $t.hr^{-1}$ was assumed (*pers. comm.*[17]). Diffuser throughput is limited by the dewatering mill fibre throughput capacity, which was estimated to be 79 t $fibre.hr^{-1}$ (*pers. comm.* [17]). Ash levels (*A*) were estimated to be roughly 2% of the total mass of sugarcane, ranging from 1.7 % in dry weather to 4% in wet weather (*pers. comm.*[17]). A 30 t $ash.hr^{-1}$ capacity was assumed. Since Komati Mill recycles the clarifier mud, all the sand was expected to enter the boiler. The remaining two potential capacity constrictors are the A and C-Pans for which the throughput capacities were estimated to be 70 tons pol (sucrose equivalent) and 13 t non-pol $hour^{-1}$, respectively (*pers. comm.* [17]). Table 5.9 provides a summary of the inputs used.

5.3.3.8 Extraction and exhaustion component inputs

The two major mill components modelled by CAPCONN are extraction (*E*) and exhaustion (*X*). Extraction was modelled using Equation 4.21. Values of 96% and 99% were used for E_{max} and E_{min} (*pers. comm.*[16]). Values of 10% and 16%, 1% and 10% were used for F_{max}, F_{min}, A_{max} and A_{min}, respectively. These values were based on the sugarcane composition table input information discussed in Section 5.3.

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[16] A. Williamson, Mill Manager, Komati Mill, Komatipoort, South Africa, March 2006

Exhaustion was modelled using Equation 4.22. Values of 86% and 88% were used for X_{max} and X_{min}, respectively (Anon, 2005). Non-sucrose (*NS*) values of 1% and 5% were used for NS_{max} and NS_{min}, based on the sugarcane composition table input information discussed in Section 5.3.

Inversion was modelled using Equation 4.9. Values of 0.1%, 0.24% and 0.05% were used for c_3 in the clarifier, evaporator and A, B and C-Pans respectively (Shaffler, 1994). In general, a smoother flow of produce in the mill reduces total sucrose inversion losses to between 1.0% and 1.5% while a few start-stops would raise it to between 3.0% and 4.0% (*pers. comm.*[17]).

5.3.4 Cost Inputs

This section summarises the fixed cost (FC) and variable cost (VC) inputs for each component of the Komati Mill supply chain. The derivation of dual price is also discussed. Two general cost inputs are the agronomic input costs and the cost of dealing with soil in the mill. Agronomic costs of R 8 t^{-1} and R 22 t^{-1} for green and burnt sugarcane, respectively, were obtained from the Trashing Model. These values were later estimated to be in the order of R 100 t^{-1} (*pers. comm.*[18]) and hence could be significantly underestimated. The maintenance cost for the milling of soil was assumed to be R 100 t^{-1} as estimated by Purchase and de Boer (1999).

5.3.4.1 Harvest, loading and transport costing

Three types of mechanical harvesters are most commonly used in South Africa, namely the Case IH, Claas and Cameco. The Cameco is considered to be the most suitable for use by harvest contractors in Malelane (*pers. comm.*[19]), costing approximately R 2.2 million per unit. The transport component of the Trashing Model was used to estimate the mechanical harvester FC. For a purchase price of 2.2 million, a machine operator cost of R 86 000 pa and R 71 200 licence fees, the FC was 10 177 R.wk^{-1}, per harvester.

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[17] S. Davis, Mill Process Engineer, SMRI, Durban, South Africa, January 2006
[18] B. Purchase, Retired SMRI Manager, SMRI, Durban, South Africa, April 2006
[19] L van Staden, Harvest contractor, Komatipoort, Mpumalanga, South Africa, March 2006

A mechanical harvesting VC of R 20 t^{-1} and R 17 t^{-1} were used for green and burnt sugarcane respectively (*pers. comm.*[20]).

Manual harvesting costing involves both FC and VC. The FC includes UIF, rations, housing, electricity, water, working equipment and transport. FC can be estimated as roughly equal to 50% of the VC (*pers. comm.*[21]). A VC of R 11.13 t^{-1} and R 4.53 t^{-1} was used for green and burnt sugarcane respectively, obtained from the Trashing Model. This corresponds to a wage of R 30 and R 38 per day. Assuming 7 days of the week are worked, and a FC of R 30 $day^{-1}.man^{-1}$, the weekly FC = R 105 man^{-1}. Overtime payments were not considered.

A loading VC of R 1.93 t^{-1} and FC of R 2 342 $week^{-1}$ were obtained from the Trashing Model. The FC was based on a machine price of R 330 000. Transport costing was estimated using the Trashing Model, which makes use of an extensive spreadsheet to calculate transport costs accounting for depreciation and interest. A combined purchase price of R 1.4 million was used for the truck and trailer unit (*pers. comm.*[21]). Other FC included a machine operator cost of R 86 000 pa and a R 71 200 licence fee. This resulted in a FC of R 7 735 $week^{-1}$ and VC of R 10 t^{-1}. The VC was increased from R 10 t^{-1} to R 15 t^{-1}, proportionally to the FC increase of the initial Trashing Model truck cost to the current estimated cost of R 1.4 million. Table 5.9 provides a summary of the costing inputs described in this section, as well as offloading costing.

5.3.4.2 Offloading costing

The FC of all the mill offloading equipment was assumed to be R 50 million and the equipment was assumed to have a lifespan of 10 years. Dividing by 520 weeks, the FC is roughly R 100 000 $week^{-1}$. A VC of R 0.01 t^{-1} was assumed for maintenance and electricity based on a Komati Mill maintenance cost report (*pers. comm.*[22]).

[20] E. Meyer, Agricultural Engineer, SASRI, Mt Edgecombe, Durban , South Africa, August 2005
[21] R. Giles, Agricultural Engineer, Crickmay and Associates, Pietermaritzburg, South Africa, April 2006
[22] A. Williamson, Mill Engineer, Komati Mill, Komatipoort, Mpumalanga, South Africa, March 2006

Table 5.9 Summary of costing inputs for harvest, load, transport and offloading operations

Component	Harvest treatment	Fixed cost ($R.wk^{-1}.unit^{-1}$)	Variable cost ($R.t^{-1}$)
Agronomic component	Burn	-	22
Agronomic component	Green	-	8
Mechanical harvesting	Burn	10 177	17
Mechanical harvesting	Green	10 177	20
Manual harvesting	Burn	105	4.53
Manual harvesting	Green	105	11.13
Loading	-	2 342	1.93
Transport	-	7 735	15
Mill offloading equipment	-	100 000	0.01

5.3.4.3 Mill costing

Mill costing information is generally confidential and for the purposes of this case study, mill costing values were based largely on assumptions. Each component in the mill was considered to have the same FC of R 200 000 $week^{-1}$. This was estimated by assuming each component costs R 100 million and operates for 10 years. The theoretical value of R 100 million was based on the cost of R 130 million to install a new boiler at Komati Mill (*pers. comm.*[23]).

It was estimated that 80% of mill VC were attributed to the mill front end (*pers. comm.*[23]). The VC of preparation, extraction and boiling should therefore be 80% of the total mill operational cost.

A Komati Mill maintenance cost report showed a maintenance cost range for preparation of between R 1.4 million and R 2 million pa from 2001 to 2005. It was assumed that billets have a lower VC as they can be prepared faster than whole stalk sugarcane. For a 2.2 million ton season the whole stalk VC was assumed to be R 1 t^{-1}, increased by 10% to account for operational VC. The billet cost was based on the lower maintenance cost of R 1.4 million, and was increased by 10% to R 0.7 t^{-1} to account for

[23] S. Davis, Mill Process Engineer, SMRI, Durban, South Africa, January 2006

operational VC. The average diffuser maintenance cost from 2001 to 2005 was R 5 million. The diffuser VC used was R 2.27 t^{-1} (R 5 million ÷ 2.2 million tons per season).

The mill maintenance cost report showed boiler ash handling amounting to R 320 000 pa which is equivalent to R 0.145 t^{-1} of sugarcane for 2.2 million tons of sugarcane per season. For an average A of 2.5%, the VC of processing ash amounts to R 9 t^{-1} of ash. The mill maintenance cost report shows boiler maintenance cost amounts to R 2.8 million. This cost was assumed to be a function of the amount of bagasse burnt. For a 2.2 million ton season it costs R 1.27 $R.t^{-1}$ of sugarcane and for a fibre content of 20%, this is equivalent to R 6 t^{-1} of fibre. The total VC is the sum of the ash and fibre costs.

The Komati Mill maintenance cost report was also used to estimate mill back end costs. The juice heating, clarification and evaporation costs were based on the $R.t^{-1}$ sugarcane, not on the $R.t^{-1}$ mixed juice. This simplified the effects of sugarcane quality and imbibition variation. The A, B and C-Pan VC was converted from $R.t^{-1}$ sugarcane to $R.t^{-1}$ brix (sucrose + non-sucrose). The cost of the B-Pan was included in the A and C-Pan costs. Similarly, the crystalliser cost of R 0.055 t^{-1} sugarcane was converted to R 0.36 t^{-1} brix (for 15% brix). The cost for the A and C crystallisers was therefore R 0.2 t^{-1} brix, which included the B crystalliser cost. A single figure was used to represent the combined cost of centrifuging in the A, B and C stations. The cost units described above were selected in order to simplify costing calculations.

Produce residence times within each component were obtained in order to calculate the stock cost, described by Equation 4.11. Estimated values were used for the purposes of this project, which were obtained from consultation, shown in Table 5.10 (*pers. comm.*[26]). Table 5.10 shows the mill costing for a 2.2 million ton season.

Table 5.10 Komati Mill costing based on a 2.2 million ton season (*pers. comm.*[24])

	FC ($R.week^{-1}$)	VC ($R.t^{-1}$ sugarcane)	Equivalent cost ($R.t^{-1}$ sugarcane compound)	Component residence time (minutes)
Preparation of billeted sugarcane	200 000	0.7	-	-
Preparation of wholestalk sugarcane	200 000	1	-	-
Diffuser extraction	200 000	2.27	-	-
Boiler furnace	200 000	0.145	-	
Juice heating	200 000	0.030	-	12
Clarification	200 000	0.040	-	18
Evaporation	200 000	0.20	-	24
Pans	200 000	0.20	0.66 $R.t^{-1}$ brix per station	30
Crystallisers	200 000	0.055	0.2 $R.t^{-1}$ brix per station	54
Centrifuging	200 000	0.23	1.5 $R.t^{-1}$ brix	24

5.3.4.4 Determination of component dual price

The dual price (*DP*) has been defined as the required input cost to increase or decrease the throughput capacity of a SC component, or a series of components. The dual price for each component was calculated as follows:

- Manual harvesters were assumed to work for 6 hours a day, 7 days a week over a 38 week season, totalling 1596 seasonal hours. For a y_{unit} of 1 $t.hr^{-1}$ each labourer cuts 1596 t $season^{-1}$. Multiplying the t $season^{-1}$ by a R 4 t^{-1} gave the seasonal *VC*. For a FC of R 105 $week^{-1}$ the TC per labourer was R 10 374 $season^{-1}$, which equaled the dual price.

[24] A. Williamson, Mill Engineer, Komati Mill, Komatipoort, Mpumalanga, South Africa, March 2006

- As a result of the larger y_{unit} of mechanical harvesters, the y_H could only be increased in relatively large increments. The following inputs were assumed. The y_{unit} = 60 $t.hr^{-1}$, VC = R 17 t^{-1} and FC = R 10 177 $week^{-1}$. For a 40% downtime, TC was 29 913 398 $harvester^{-1}$. The Dual price was R 49857 $t^{-1}.hr^{-1}$ (R 29 913 398 $harvester^{-1}.season^{-1}$) / (60 $t.hr^{-1}$).
- The same principle used to calculate the mechanical harvesting dual price, was used for the loading and transport components. The seasonal *TC* was divided by the $t^{-1}.hr^{-1}.unit^{-1}$, which gave R 140624 $t^{-1}.hr^{-1}$and R153704 $t^{-1}.hr^{-1}$ for the loading and transport components, respectively.
- Offloading and mill costing was based on theoretical cost figures. An initial estimate of the dual price was estimated at 300 000 $ per ton sugarcane per hour (Kent *et al.*, 1999). This is equivalent to R1 320 000 $t^{-1}.hr^{-1}$. This value was divided equally between each of the milling components included in CAPCONN.

The required modelling inputs were sourced from literature, consultation and where necessary they were assumed. The modelling algorithms for mill process were developed specifically to assess mechanisation impacts.

6 MODEL EVALUATION

Chapter 5 described the development of the modelling algorithms and the sourcing of modelling inputs. This chapter discusses three main topics: (1) configuring the model with inputs obtained from industry, (2) validating the integrity of the model through a sensitivity analysis and (3) where possible, verifying model outputs with observed data. As a result of the complexity of this model, configuration and integrity validation were handled together. It was decided that the best means of validating CAPCONN's inputs and verifying CAPCONN's outputs was to use an independent data source of Komati Mill values. This is because sugarcane quality and mill performance characteristics are highly mill specific. Hence CAPCONN transport and mill data were compared to SLIP and SMRI data.

6.1 Model Configuration and Integrity

This section assesses how well the model represents the physical system by confirming input data and comparing output data with independent observed data. Confirming input data provides an indication of data integrity, while comparing output data indicates model accuracy. Both input and output data need to be compared with external data that are independent of any data used in the model. Unfortunately, there was a limited availability of observed data for field to mill output verification.

6.1.1 Transport capacity configuration

Loading and transport operations were assessed based on transport utilisation information from the Sugar Logistics Improvement Programme (SLIP) (*pers. comm.*[25]). An average load time of 0.59 hours was measured at Komati Mill, which was lower than the 1 hour per truck assumed in the model. The average load rate has been measured as 1.31 $minutes.t^{-1}$, which corresponds to 45.8 $t.hr^{-1}$. This is significantly higher than the 22 and 33 $t.hr^{-1}$ assumed in the model, for non-slewing and excavator type slewing loaders respectively (See Section 5.3.3.4).

[25] R. Giles, Bioresources Engineer and Logistics Consultant, Crickmay and Associates, Pietermaritzburg, South Africa, April 2006

Inconsistencies may exist between the 2003 and 2005 SLIP data, which measured 88 trucks in 2003 and 65 trucks in 2005 respectively. The CAPCONN transport capacity of 7.77 $t.hr^{-1}.truck^{-1}$ corresponded well with the 2003 SLIP recorded industry average of 7.7 $t.hr^{-1}.truck^{-1}$. CAPCONN input values were obtained through consultation at Komati Mill. The 2003 SLIP transport capacity for Komati Mill was measured at 6.69 $t.hr^{-1}$, which implied that CAPCONN overestimated transport utilisation by 10%.

6.1.2 Assessment of mill performance

CAPCONN mill process trends were compared to measured data recorded by SMRI in 2005. (The complete Komati Mill report is shown in the Appendix). CAPCONN outputs were compared to observed data of (1) CAPCONN input and output data ranges and (2) seasonal trends in CAPCONN input and output data. The comparison of modelled and observed model input and output data ranges served to evaluate the accuracy of the CAPCONN outputs.

"Input data" for the model consist primarily of sugarcane composition data. The 2005 observed data shows a seasonal sucrose range of 11.60% to 15.52%, which was encompassed by the CAPCONN input range of 11.0% to 16.0%. The CAPCONN fibre range was 12.5% to 14.5%, while the observed range was 12.14% to 15.97%, hence the CAPCONN range was narrower. Similarly the CAPCONN non-sucrose range of 2.6% to 2.8% was narrower than the measured observed non-sucrose range of 2.41% to 3.69%. Although some of the input ranges do not match the observed data, the CAPCONN inputs are, in the author's opinion, of suitably similar magnitude. CAPCONN ash levels were significantly over-estimated at 1.3%, while the SMRI data show an actual range of 0.21% to 0.59%. This overestimation could be a result of incorrect assumptions of the performance of the rock and trash removal system and that soil levels in the Komati Mill region are not as significant as in KwaZulu-Natal. The difference in soil level may be a result of differing harvest practice, soil type and/ or rainfall.

"Output data" for the model consist of mill component performance coefficients. Figure 6.1 shows the CAPCONN and measured industry extraction and exhaustion ranges.

Equations 4.21 and 4.22 require a maximum and minimum range in extraction and exhaustion. A seasonal extraction range of 96% to 99% was used in Equation 4.21 and the model output range was 98.6% to 98.8%. The observed data of 97.6% to 98.5% showed a greater seasonal variation compared to CAPCONN. The CAPCONN extraction model input range was suitable, but the output range was too narrow. An 86% to 88% range in exhaustion was assumed for the exhaustion equation, based on seasonal averages. The model output rage was 87.06% to 87.20% compared to the observed data range of 81.73% to 88.97%. This shows that the CAPCONN range may have been too narrow, especially overestimating the lower values of the range. The CAPCONN output range was within the SMRI data range, but it was significantly narrower. Therefore, CAPCONN output data for the Komati analysis are probably not accurate.

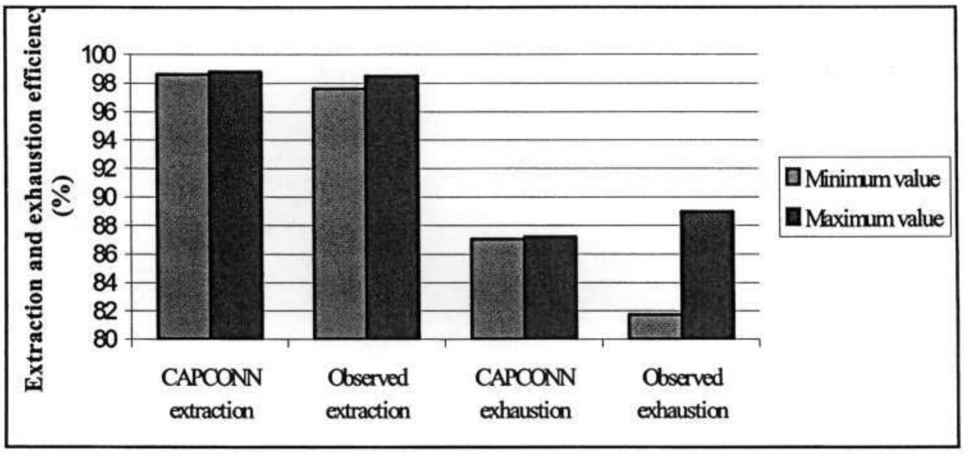

Figure 6.1 Comparison of CAPCONN and observed extraction and exhaustion ranges

The comparison of seasonal data trends served to evaluate the authenticity of CAPCONN outputs. Figure 6.2 shows the observed sucrose, non-sucrose and fibre contents for the Komati Mill 2005 season. The sucrose trend corresponded with the trend shown in Table 5.1, peaking in the midseason. The observed fibre levels followed a linearly increasing seasonal trend. The CAPCONN fibre input trend was inversely correlated to the sucrose trend and therefore underestimated the fibre contents in the late season. The CAPCONN non-sucrose seasonal trend sufficiently represents the actual trend shown in Figure 6.2 since non-sucrose reduces from early to mid season and then rises to a maximum in the late season. Seasonal ash level trends were not included as the observed ash levels are highly variable and significantly lower than the CAPCONN ash levels.

Figure 6.3 shows the observed seasonal extraction trend and CAPCONN extraction estimates. The observed extraction trend exhibited a steady decreasing extraction rate, which corresponds to the linearly increasing fibre levels. Similarly, in CAPCONN the seasonal extraction efficiency, is concave which corresponds with the concave fibre trend used in CAPCONN.

Figure 6.4 shows the observed exhaustion at Komati Mill in 2005 as well as CAPCONN exhaustion estimates. The observed data peak at mid-season, and are lowest in the late season. This trend corresponds to that in the CAPCONN seasonal exhaustion efficiency. The seasonal trend in the CAPCONN calculated exhaustion efficiency is inversely correlated to the non-sucrose % trends in Table 5.1, which is the expected trend described by Equation 4.2.2. Figure 6.5 shows the plot of the CAPCONN exhaustion efficiency vs. CAPCONN non-sucrose %. The correlation coefficient for both of the two lines is -1 which confirms linearity. The reason for the existence of two lines is that the exhaustion data is not symmetrical on either side of the mid-season values, while the non-sucrose data is. The correlation coefficient between the 2005 observed exhaustion efficiency and the CAPCONN non-sucrose %, Figure 6.6, is -0.83 which indicates a significant degree of linear correlation. This correlation reinforces the validity of Equation 4.2.2, showing exhaustion efficiency is comprehensively modelled as a function of non-sucrose % alone.

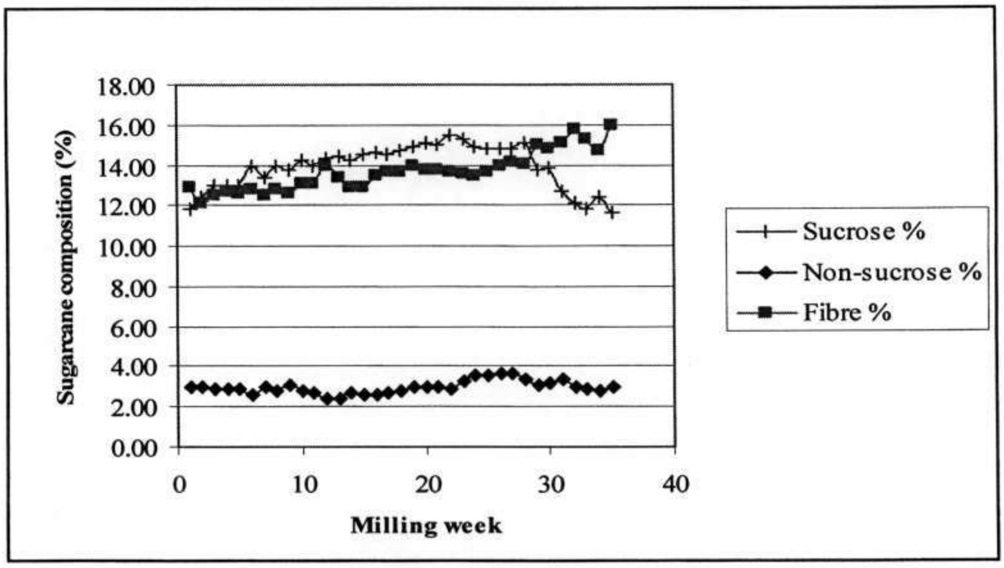

Figure 6.2 The 2005 Komati Mill observed sugarcane quality information

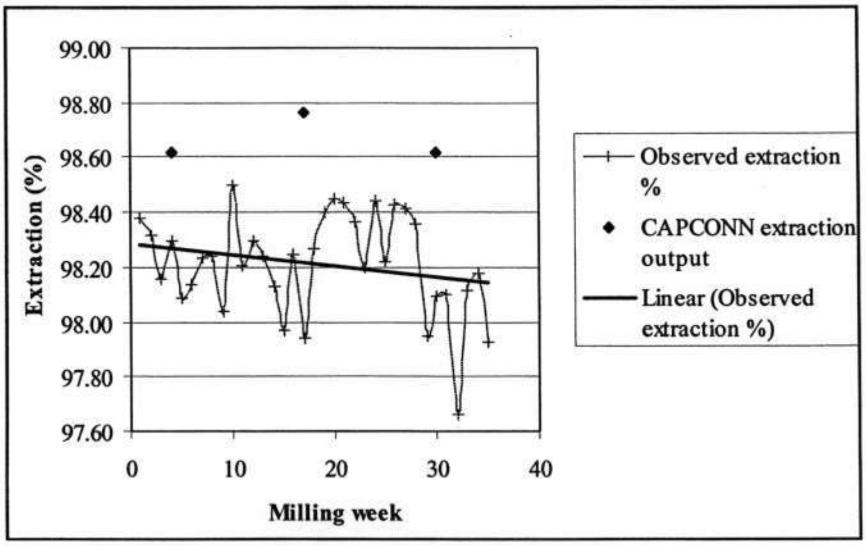

Figure 6.3 2005 Komati Mill observed extraction % data and CAPCONN extraction % data

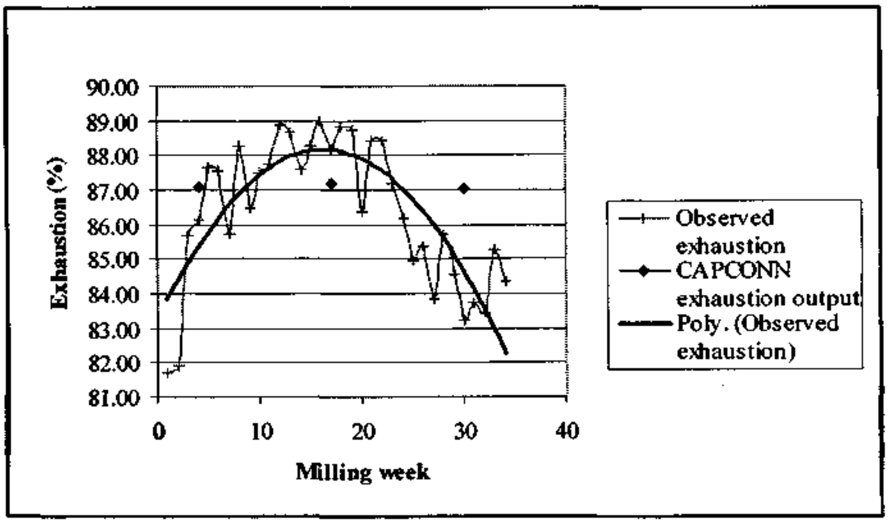

Figure 6.4 2005 Komati Mill observed exhaustion % data and CAPCONN exhaustion % data

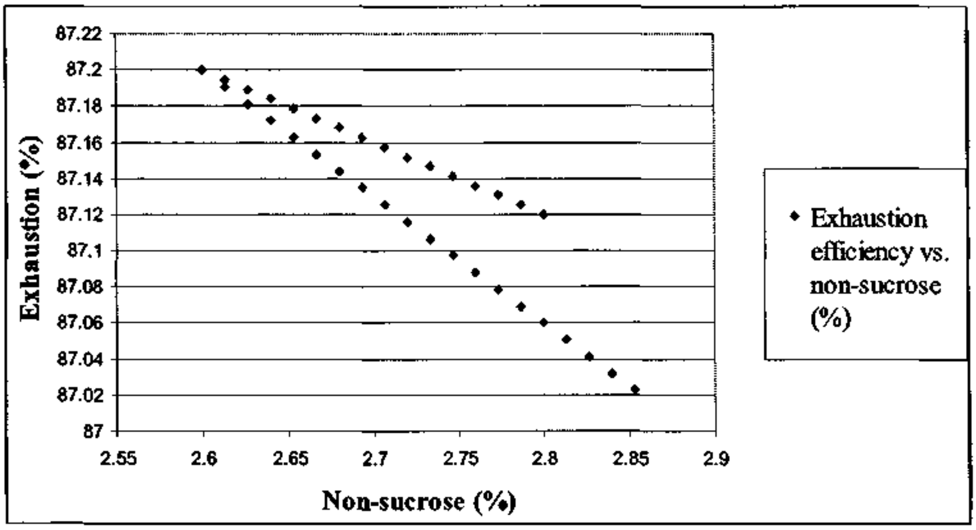

Figure 6.5 CAPCONN exhaustion efficiency vs. CAPCONN non-sucrose %

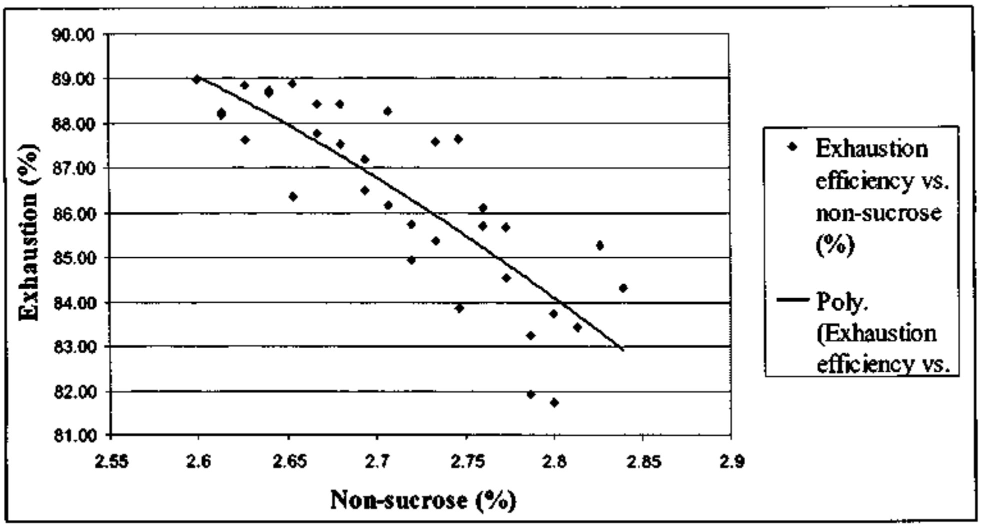

Figure 6.6 Plot of 2005 observed exhaustion (%) vs. CAPCONN non-sucrose (%)

6.1.3 Assessment of economic outputs

A comparison of total production cost provides a means of assessing CAPCONN's representation of the economics of the integrated supply chain. The best available estimate of production cost was the industry average sugar price, used to determine the recoverable value (RV) (*pers. comm.*[26]). The 2005 sugar price increased consistently throughout the season. However, the sugar price does not provide an indication of the cost to produce each ton of sugar in the mill and therefore cannot be compared to CAPCONN production cost estimates. CAPCONN estimated that sugar production costs ($R.t^{-1}$) were highest at the start of the season when sucrose content was lowest and at a minimum during the mid season when sucrose content peaked. This is because total production costs (R) are consistent throughout the season while sugar production ($t.hr^{-1}$) varies.

Another means of verifying CAPCONN's economic outputs is to compare cost outputs to those obtained through other studies. Ahmadi *et al.* (2000) conducted a trial to evaluate agronomic and cost factors related to mechanical burned and green sugarcane harvesting in Swaziland, a neighbouring region to Komati Mill. The results showed that VC for both mechanical harvesting scenarios were slightly lower than for the existing manual cut system. The CAPCONN VC of mechanical harvesting was higher than that

[26] S. Davis, Mill Process Engineer, SMRI, Durban, South Africa, January 2006

of manual harvesting, the reason for the difference is attributed to a difference between the labour rates and fuel price in Swaziland, and those used by CAPCONN in this study. This difference in output is purely attributed to the CAPCONN inputs used, and is independent of the functionality of the CAPCONN model framework.

CAPCONN estimated the total production cost of sugar to be half of the actual value of around 1500 $R.t^{-1}$ (*pers. comm.*[27]). The major reasons for this difference are that (1) the profits of the growers and hauliers, which increase production costs, are not included in CAPCONN (2) most of the mill FC and VC were assumed and (3) the agronomic cost in CAPCONN was only included in the stock cost calculation. The agronomic cost should be added to the VC in order to compare production costs with industry values. Agronomic operations and associated costs are outside of the scope of this dissertation and have therefore at this stage been omitted.

6.2 Model Sensitivity Analysis

A sensitivity analysis was used to assess the integrity of CAPCONN by testing the operational principles. This was done by assessing the sensitivity of CAPCONN outputs to changes in the driver variable inputs. A case study is not adequate to do this, as the model is run once for each scenario, providing no insight into variable sensitivity. One method to assess the integrity of a model is to perform sensitivity analysis. The response of CAPCONN output with respect to changes in selected variables by various increments was investigated. The late season (dry weather) manual harvesting of burnt sugarcane was selected for the sensitivity analysis, and outputs were intuitively evaluated against real expectations.

Trash (*TSH*) was selected as a suitable variable for evaluating field to mill components, having an impact on harvest (y_H), loading (y_L) and transport (y_T) capacity. It should be noted that *TSH* was used to represent the combined tops and trash value as explained in Section 5.3.3 The sensitivities of manual y_H, y_L, y_T and production cost to a 10% variation in *TSH* were assessed. The results are discussed in Section 6.2.1.

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[27] A. Williamson, Mill Manager, Komati Mill, Komatipoort, Mpumalanga, South Africa, March 2006

Five sugarcane composition variables were selected for sensitivity analysis of mill component operation. These were sucrose (*S*), non-sucrose (*NS*), *TSH*, soil (*A*) and HTCD. The sensitivities of extraction (E), exhaustion (X), sugar production ($t.hr^{-1}$) and boiler capacity utilisation (CU_B) were assessed. The *S* and *NS* in the stalk were varied by 10%, and trash % and soil % were adjusted by 10% after harvest and loading, respectively. The results are discussed in Section 6.3.2.

6.2.1 Field to mill and production cost sensitivity to trash content

The impacts of varying trash amounts (*TSH*) were simulated throughout the supply chain. In this section the relationships of manual harvest, load and transport component capacity to *TSH* are firstly derived. The trends in the relationships are then discussed.

Before any processing occurs, the stalk percentage of sugarcane and sugarcane density are inversely correlated to *TSH*. The unit y_H is inversely correlated to *TSH*. The harvest stalk throughput rate is therefore affected by two factors relating to *TSH*, namely composition and harvest rate. CAPCONN accounts for trash impacts on manual harvest capacity as discussed in Section 4.3.3. Since a *TSH* of 4% and 10% was used for manual burnt and green sugarcane harvesting respectively, a linear relationship was used to approximate trash impacts on the unit y_H. The burnt harvest rate and green harvest rate are 6 $t.day^{-1}$ and 4 $t.day^{-1}$, respectively. Equation 6.1 was used to determine the sensitivity of y_H to *TSH*.

$$\Delta y_H = -\Delta TSH \div 100 \times (6-4) \div (10-4) \qquad (6.1)$$

Loading (y_L) and transport (y_T) component capacities are inversely correlated to sugarcane density. Density impacts on y_L and payload (ρ) were assumed to be linear. Based on information from Section 4.3.3 y_L and ρ sensitivities were estimated by Equations 6.2 and 6.3 below. Values of 22 and 17.6 $t.hr^{-1}.unit^{-1}$ were used for burnt and green sugarcane loading, respectively. A 27.7 ton and 20.7 ton ρ were used for burnt and green sugarcane, respectively. A 4% to 10% trash range was assumed for loading and transport. The effect of lodging on density was not included.

$$\Delta y_L = -\Delta TSH \div 100 \times (22 - 17.6) \div (10 - 4) \quad (6.2)$$

$$\Delta y_T = -\Delta TSH \div 100 \times (27.6 - 20.7) \div (10 - 4) \quad (6.3)$$

Table 6.1 and Figure 6.7 show the sensitivity of harvest, load and transport capacity to a 10% change in *TSH*. This corresponded to a 0.06 unit change in magnitude of trash for the default value of 6% trash.

Table 6.1 Changes in CAPCONN outputs for a 10% variation in trash % sugarcane

	Model value	% change	Harvest rate (t/day)	Loader rate (t/hr)	Payload (tons)	Transport (t/hr)	R/t sugarcane
Normal case			6.0	22.0	27.6	7.77	483.0
Trash %	4%	10%↑	-0.33	-0.20	-0.25	-0.12	+0.41
		10%↓	+0.33	+0.20	+0.25	+0.25	-0.41

The trends are as expected for each scenario, with increasing *TSH* reducing system capacity by reducing sugarcane density and increasing biomass. The y_H was most sensitive to *TSH*, followed by ρ and finally y_L. The sensitivity of y_T to *TSH* was assessed by determining the sensitivity of the unit y_T to ρ. The only variable that showed a non-linear sensitivity was transport unit capacity (t.hr^{-1}.unit^{-1}).

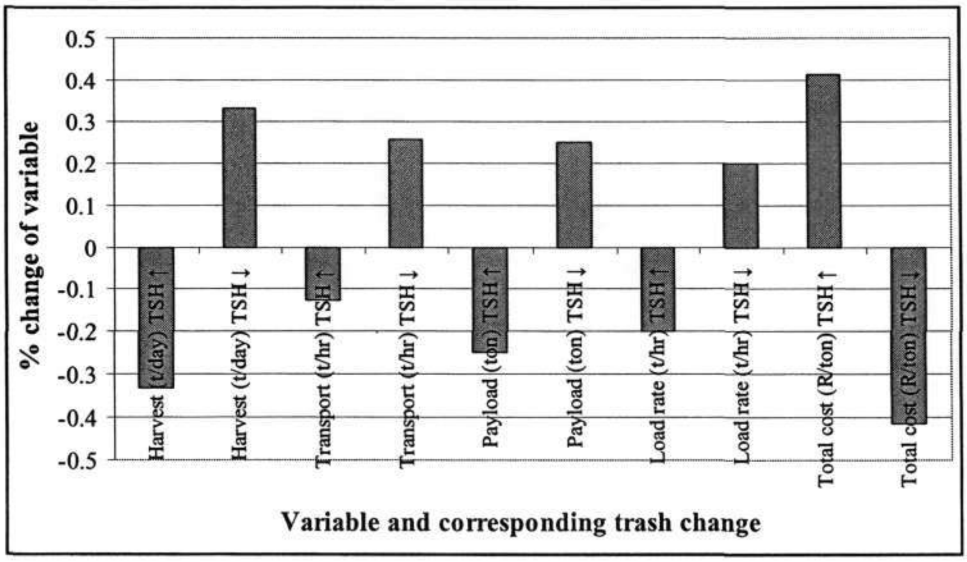

Figure 6.7 Capacity and production cost sensitivity to a 10% trash variation

The sugar production cost ($R.t^{-1}$) was obtained from the diagnostics output sheet, the calculation of which is explained in Section 4.4. The production cost was seen to be inversely correlated to *TSH*. This is because *TSH* occupies sugarcane mass, effectively displacing *S*, and *TSH* furthermore reduces *S* extraction. *TSH* did not impact on FC and VC, however the decrease in *S* throughput decreased the $R.t^{-1}$ production cost.

6.2.2 Mill performance sensitivity to sugarcane quality and HTCD

Table 6.2 and Figures 6.8, 6.9, 6.10 and 6.11 show mill operation sensitivity to a 10% variation in sucrose (*S*), non-sucrose (*NS*), trash (*TSH*), ash (*A*) and harvest to crush delay (HTCD).

Figure 6.6 shows that simulated E % was more sensitive to *TSH* than to *A*. The results correspond to the trends concluded by Cárdenas and Diez (1993) which are discussed in 4.3.2.2. The reason E % was less sensitive to *A* although *A* carries a greater weight in Equation 4.20, is that *TSH* occupies a higher proportion of the harvested sugarcane composition. Hence a 10% change in *TSH* will be proportionally larger than a 10% change in *A*. Changes in *S* and *NS* in Table 4.3 impact on the moisture content and do not reduce the percentages of *F* and *A*. Hence a variation in *S* has no impact on E % or X %, E % being a function of *F* and *A*, and X a function of *NS*. E % is not sensitive to HTCD which only influences *NS* %.

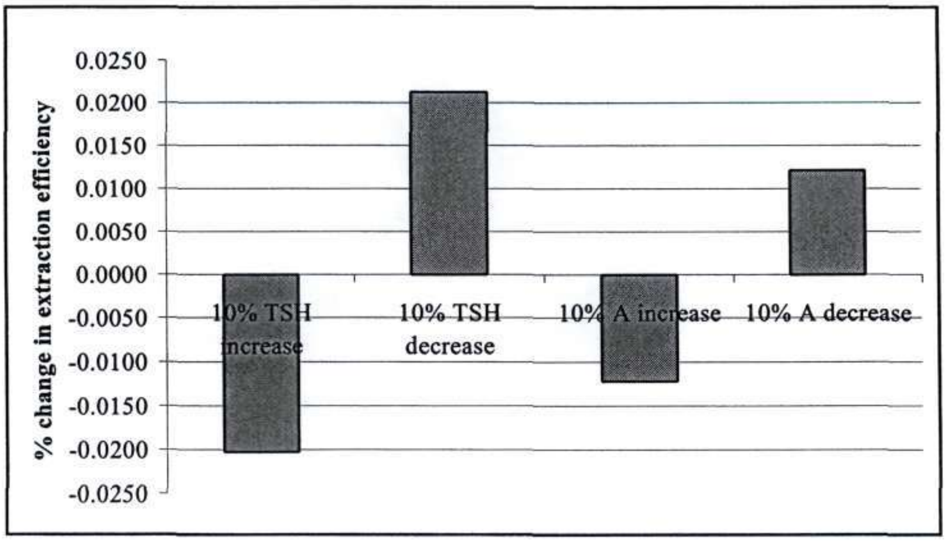

Figure 6.8 Sensitivity of extraction % to a 10% variation of trash and soil

Table 6.2 Changes in model milling outputs for a 10% variation in model inputs

	Model value		Extraction %	Exhaustion %	t/ hour sugar	Boiler capacity utilisation
Normal case			0.9860	0.8706	41.64	17.3%
Sucrose %	12.6%	10%↑	-	-	45.80	-
		10%↓	-	-	37.47	-
Non-sucrose %	2.87%	10%↑	-	0.8692	41.57	-
		10%↓	-	0.8721	41.71	-
Trash %	4%	10%↑	0.9860	-	-	-
		10%↓	0.9864	-	-	-
Soil %	2%	10%↑	0.9861	-	41.64	20.0%
		10%↓	0.9863	-	41.65	14.7%
Harvest to crush delay	45 hours	10%↑	-	0.8706	41.58	-
		10%↓	-	0.8707	41.70	-

Figure 6.9 shows the sensitivity of X % to *NS* and the HTCD of 45 hours. The simulated X % was inversely correlated to *NS* which is an expected trend (*pers. comm.*[28]). It is evident that a 10% change in HTCD generated a significantly lower change to *NS*. It is also evident that *NS* was insensitive to *S*, *TSH* and *A* changes.

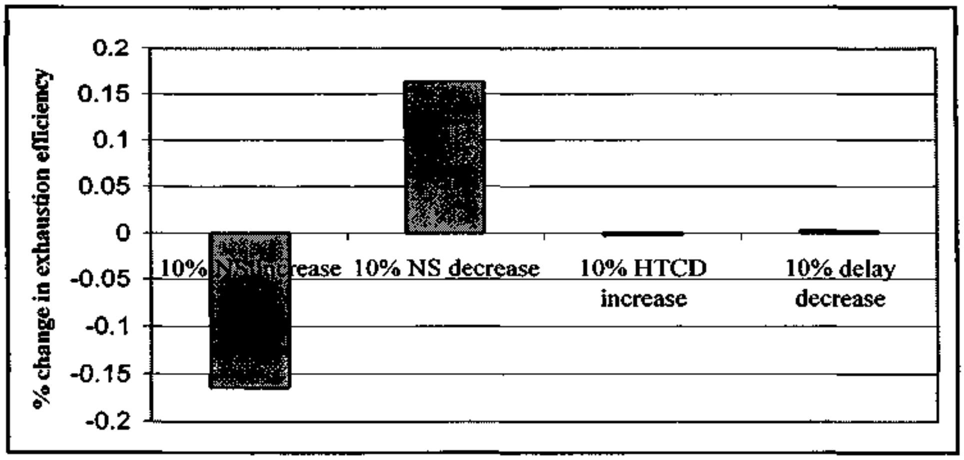

Figure 6.9 Sensitivity of extraction to a 10% variation of non-sucrose % and HTCD

[28] S. Davis, Mill Process Engineer, SMRI, Durban, South Africa, October 2005

Figure 6.10 shows the sensitivity of the sugar production rate (t.hr^{-1}) to changes in sugarcane quality and the HTCD. *S* impacted significantly on sugar production, relative to *NS*, *A* and HTCD. The sugar production rate was correlated to *S* and was inversely correlated to *NS*, *A* and HTCD which were the expected trends. Sugar production was inversely proportional to *A* and *NS* as a result of the associated impacts of these compounds on E % and X %.

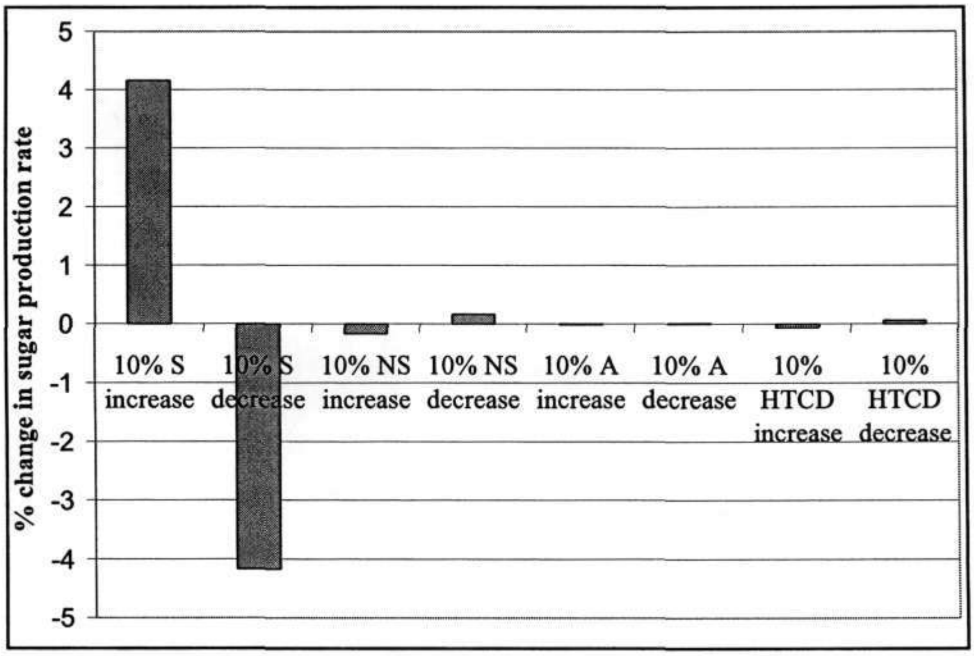

Figure 6.10 Sensitivity of sugar production rate to a 10% variation of sucrose, non-sucrose and soil content, and HTCD

Figure 6.11 shows that the simulated boiler capacity utilisation (CU_B) was sensitive to *A*, changing by 15% for a 10% change in soil %. CU_B was not sensitive to *S*, *NS*, *TSH* or HTCD, being solely a function of *A* alone.

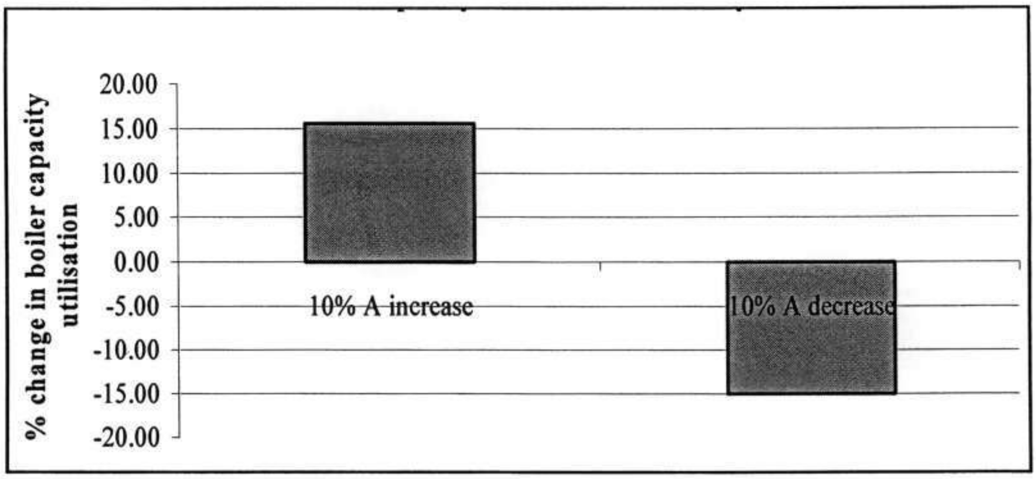

Figure 6.11 Sensitivity of boiler capacity utilisation to a 10% variation of soil %

6.3 Conclusions

CAPCONN inputs and outputs have been compared to industry measured data, termed observed data. Relatively few data comparisons were available for field to mill processes, and no comprehensive means of evaluating production cost trends were available. According to SLIP observed data, CAPCONN overestimated transport capacity by 10%. CAPCONN output data was compared to the observed 2005 SMRI data in terms of seasonal data range and trend. The simulated extraction % and exhaustion % ranges were within the observed range and the seasonal trends did not correspond well to SMRI data. However, CAPCONN output trends and observed operational trends corresponded to sugarcane quality trends. This suggests that if the same quality curves were used, the same mill performance curves may have been obtained. The costing evaluation was inconclusive, as the available industry costs did not include the same cost variables used in CAPCONN.

The sensitivity trends of all simulated variables followed intuitive expectations. The equation for transport unit capacity exhibited a non-linear relationship with transport capacity, as shown in Figure 6.7. All other variable changes were equal in magnitude and opposite in sign, showing the linearity of CAPCONN variable relationships. The magnitude and direction of harvest, load and transport capacity change are perceived to be representative as these components were significantly simpler to model compared to mill processes. In the mill, the trends of changes in component capacity and performance variables are perceived to be accurate. Further refinement of the algorithms used by CAPCONN would allow mill component capacity and performance to be more accurately determined. Knowing the cost associated with changes in component capacity or performance would allow comparison of the financial significance of variable sensitivity.

7 A SUPPLY CHAIN CASE STUDY: MECHANISATION AT KOMATI MILL; RESULTS AND DISCUSSION

This chapter discusses the results of the case study which are presented in table form. Table 7.1 shows CAPCONN estimates of capacity utilisation (*CU*) for the existing system (Scenario 1) inputs used in all three scenarios. The loading and transport component capacities for Scenarios 2 and 3 were adjusted to run with a suitable truck fleet size. For green whole stalk harvesting, the truck fleet capacity was increased by 22 trucks and for mechanical harvesting it was decreased by 25 trucks. Table 7.4 shows estimates of *CU* after these system adjustments had been made.

Table 7.2 shows general model outputs representing the existing system. These include the estimated maximum throughput $t.wk^{-1}$, a total cost breakdown, estimated diffuser recovery and exhaustion. A $t.hr^{-1}$ of sugar and a $R.t^{-1}$ sugar value were calculated. The $t.hr^{-1}$ of sugar was calculated by multiplying the sugarcane throughput rate with sucrose content and the E and X coefficients. The $R.t^{-1}$ sugar was then calculated by dividing the total cost $R.hr^{-1}$ by the $t.hr^{-1}$. Table 7.5 shows the general outputs after making the system capacity adjustments described above.

Tables 7.3 and 7.6 show the total cost (*FC* + *VC* + *STC*) for each component in the SC. The tables show the unadjusted and adjusted inputs respectively, the system capacity adjustments being those described above.

7.1 General Observations of Dry Weather Scenarios

The required weekly flow of 58 000 $t.wk^{-1}$ (for a 38 week milling season crushing 2.2 million tons of sugarcane) has been met for the current systems of manual burnt sugarcane harvesting, shown in Table 7.2. This was confirmed by TSB employees during consultation, who stated Komati Mill has an over-designed sugarcane throughput capacity. It is further confirmed by Enslin (2003), who stated that by 2006, Komati Mill is planned to have a 2.6 million ton seasonal crush capacity.

Table 7.1 Capacity utilisation (%) based on the current system at Komati Mill

Scenario	1	2	3a	3b	7	8	9a	9b	4	5	6a	6b
Season	Early season	Mid season	Late season Dry	Late season Wet	Early season	Mid season	Late season Dry	Late season Wet	Early season	Mid season	Late season Dry	Late season Wet
Harvest	Manual	Manual	Manual	Manual	Manual	Manual	Manual	Manual	Mech	Mech	Mech	Mech
Treatment	Burn	Burn	Burn	Burn	Green	Green	Green	Green	Green	Green	Green	Green
Harvest	100%	100%	100%	100%	87%	87%	87%	87%	100%	100%	100%	60%
Load	54%	54%	54%	54%	59%	59%	59%	59%				
Transport	86%	86%	86%	86%	100%	100%	100%	100%	54%	54%	54%	33%
Offloading	61%	61%	61%	61%	53%	53%	53%	53%	51%	51%	51%	31%
Preparation	65%	65%	65%	65%	61%	61%	61%	61%	54%	54%	54%	32%
Extraction	74%	63%	74%	85%	78%	69%	78%	98%	81%	71%	81%	63%
Boiler	17%	17%	17%	47%	15%	15%	15%	41%	87%	87%	87%	100%
A-Pan	61%	89%	68%	65%	51%	75%	57%	53%	60%	87%	67%	37%
C-Pan	85%	80%	88%	87%	72%	68%	75%	71%	83%	79%	86%	50%

Table 7.2 General outputs based on the current system at Komati Mill

Scenario	1	2	3a	3b	7	8	9a	9b	4	5	6a	6b
Season	Early season	Mid season	Late season Dry	Late season Wet	Early season	Mid season	Late season Dry	Late season Wet	Early season	Mid season	Late season Dry	Late season Wet
Harvest	Manual	Manual	Manual	Manual	Manual	Manual	Manual	Manual	Mech	Mech	Mech	Mech
Treatment	Burn	Burn	Burn	Burn	Green	Green	Green	Green	Green	Green	Green	Green
Total cost FC + VC + Stock Cost ($R.wk^{-1}$)	4697870	4698759	4700356	4853106	4572404	4573143	4574512	4715371	5721076	5722297	5723580	4853768
FC ($R.wk^{-1}$)	3023080	3023080	3023080	3023080	3098155	3098155	3098155	3098155	2924899	2924899	2924899	2924899
VC ($R.wk^{-1}$)	1532004	1532915	1534487	1555153	1345901	1346659	1348006	1373692	2376263	2377504	2378764	1456752
Stock Cost ($R.wk^{-1}$)	64786	64764	64789	64872	60353	60334	60356	60460	29914	29894	29917	22117
Cost of soil ($R.wk^{-1}$) (Included in total cost)	78000	78000	78000	210000	67995	67995	67995	183064	390000	390000	390000	450000
Maximum throughput before bottleneck ($t.wk^{-1}$)	60000	60000	60000	60000	52304	52304	52304	52304	60000	60000	60000	36000
Estimated extraction (%)	98.62%	98.76%	98.62%	98.33%	98.42%	98.55%	98.42%	97.98%	98.21%	98.34%	98.21%	97.54%
Estimated sugar exhaustion (%)	87.12%	87.20%	87.06%	87.09%	87.16%	87.23%	87.11%	87.17%	87.15%	87.22%	87.10%	87.16%
Estimated sugar recovery ($tons.hr^{-1}$)	37.46	54.74	41.64	40.24	31.46	45.86	35.01	32.65	36.98	53.78	41.19	23.03
$R.ton^{-1}$ sugar produced	746	511	672	718	865	594	778	860	921	633	827	1255

Table 7.3 Individual component costing (FC + VC + Stock cost) based on the current system at Komati Mill

Scenario	1	2	3a	3b	7	8	9a	9b	4	5	6a	6b
Season	Early season	Mid season	Late season Dry	Late season Wet	Early season	Mid season	Late season Dry	Late season Wet	Early season	Mid season	Late season Dry	Late season Wet
Harvest	Manual	Manual	Manual	Manual	Manual	Manual	Manual	Manual	Mech	Mech	Mech	Mech
Treatment	Burn	Burn	Burn	Burn	Green	Green	Green	Green	Green	Green	Green	Green
Harvest	445070	445070	445070	445070	483560	483560	483560	483560	1323725	1323725	1323725	843117
Load	188631	188631	188631	188631	173585	173585	173585	173585				
Transport	1416764	1416764	1416764	1416764	1300234	1300234	1300234	1300234	1405058	1405058	1405058	1044295
Offloading	102287	102287	102287	102287	102114	102114	102114	102114	101587	101587	101587	101029
Preparation	208717	207488	208717	210085	209189	208162	209189	211574	206742	205900	206742	205195
Extraction	338850	338850	338850	338851	321196	321195	321196	321198	339166	339165	339166	283800
Boiler	259292	251919	259292	279380	261227	255062	261227	285894	292844	285621	292844	284996
Juice heating	202983	202981	202983	202989	202679	202677	202679	202686	203118	203116	203118	202042
Clarification	204256	204252	204256	204264	203838	203835	203838	203849	204458	204455	204458	202963
Evaporator	214587	214583	214587	214599	212901	212897	212901	212915	214857	214853	214857	209341
A-Pan	208800	210716	209329	209172	207756	209359	208204	207924	209072	210949	209603	206142
A Crystalliser	205852	206429	206013	205977	205369	205852	205505	205436	206237	206802	206398	204545
C-Pan	206886	208806	207415	207249	205953	207558	206400	206109	206955	208835	207486	204563
C Crystalliser	203911	204492	204072	204028	203539	204025	203676	203596	204094	204663	204255	202939
Centrifuge	212983	217492	214090	213760	211268	215034	212209	211634	213162	217568	214282	208801

Table 7.4 Capacity utilisation (%) based on an adjusted system for Komati Mill

Scenario	7	8	9a	9b	4	5	6a	6b	1	2	3a	3b
Season	Early season	Mid season	Late season Dry	Late season Wet	Early season	Mid season	Late season Dry	Late season Wet	Early season	Mid season	Late season Dry	Late season Wet
Harvest	Manual	Manual	Manual	Manual	Mech	Mech	Mech	Mech	Manual	Manual	Manual	Manual
Treatment	Green	Green	Green	Green	Green	Green	Green	Green	Burn	Burn	Burn	Burn
Harvest	100%	100%	100%	89%	100%	100%	100%	60%	100%	100%	100%	100%
Load	68%	68%	68%	60%					54%	54%	54%	54%
Transport	86%	86%	86%	77%	88%	88%	88%	53%	86%	86%	86%	86%
Offloading	61%	61%	61%	54%	51%	51%	51%	31%	61%	61%	61%	61%
Preparation	70%	70%	70%	63%	54%	54%	54%	32%	65%	65%	65%	65%
Extraction	89%	79%	89%	100%	81%	71%	81%	63%	74%	63%	74%	85%
Boiler	17%	17%	17%	42%	87%	87%	87%	100%	17%	17%	17%	47%
A-Pan	59%	85%	65%	54%	60%	87%	67%	37%	61%	89%	68%	65%
C-Pan	82%	78%	85%	73%	83%	79%	86%	50%	85%	80%	88%	87%

Note: Transport capacity was increased by 22 trucks for Scenario 2 and decreased by 25 trucks for Scenario 3.

Table 7.5 General outputs based on an adjusted system for Komati Mill

Scenario	7	8	9a	9b	4	5	6a	6b	1	2	3a	3b
Season	Early season	Mid season	Late season Dry	Late season Wet	Early season	Mid season	Late season Dry	Late season Wet	Early season	Mid season	Late season Dry	Late season Wet
Harvest	Manual	Manual	Manual	Manual	Mech	Mech	Mech	Mech	Manual	Manual	Manual	Manual
Treatment	Green	Green	Green	Green	Green	Green	Green	Green	Burn	Burn	Burn	Burn
Total cost FC + VC + Stock Cost ($R.wk^{-1}$)	4958506	4959354	4960924	4925904	5526657	5527877	5529161	4659349	4697870	4698759	4700356	4853106
FC ($R.wk^{-1}$)	3268325	3268325	3268325	3268325	2731524	2731524	2731524	2731524	3023080	3023080	3023080	3023080
VC ($R.wk^{-1}$)	1543939	1544808	1546353	1406981	2376263	2377504	2378764	1456752	1532004	1532915	1534487	1555153
Stock Cost ($R.wk^{-1}$)	68243	68221	68246	63098	28870	28849	28873	21073	64786	64764	64789	64872
Cost of soil ($R.wk^{-1}$) (Included in total cost)	78000	78000	78000	187500	390000	390000	390000	450000	78000	78000	78000	210000
Maximum throughput before bottleneck ($t.wk^{-1}$)	60000	60000	60000	53571	60000	60000	60000	36000	60000	60000	60000	60000
Estimated extraction (%)	98.42%	98.55%	98.42%	97.98%	98.21%	98.34%	98.21%	97.54%	98.62%	98.76%	98.62%	98.33%
Estimated sugar exhaustion (%)	87.16%	87.23%	87.11%	87.17%	87.15%	87.22%	87.10%	87.16%	87.12%	87.20%	87.06%	87.09%
Estimated sugar recovery ($tons.hr^{-1}$)	36.09	52.61	40.16	33.44	36.98	53.78	41.19	23.03	37.46	54.74	41.64	40.24
$R.ton^{-1}$ sugar produced	818	561	735	877	890	612	799	1204	746	511	672	718

Note: Transport capacity was increased by 22 trucks for Scenario 2 and decreased by 25 trucks for Scenario 3.

Table 7.6 Individual component costing (FC + VC + Stock cost) based on an adjusted system for Komati Mill

Scenario	7	8	9a	9b	4	5	6a	6b	1	2	3a	3b
Season	Early season	Mid season	Late season Dry	Late season Wet	Early season	Mid season	Late season Dry	Late season Wet	Early season	Mid season	Late season Dry	Late season Wet
Harvest	Manual	Manual	Manual	Manual	Mech	Mech	Mech	Mech	Manual	Manual	Manual	Manual
Treatment	Green	Green	Green	Green	Green	Green	Green	Green	Burn	Burn	Burn	Burn
Harvest	521146	521146	521146	489750	1323725	1323725	1323725	843117	445070	445070	445070	445070
Load	188731	188731	188731	176080					188631	188631	188631	188631
Transport	1587964	1587964	1587964	1490362	1211567	1211567	1211567	850804	1416764	1416764	1416764	1416764
Offloading	102451	102451	102451	102264	101535	101535	101535	100978	102287	102287	102287	102287
Preparation	210541	209362	210541	211855	206742	205899	206742	205195	208717	207488	208717	210085
Extraction	339015	339014	339015	324227	339037	339036	339037	283671	338850	338850	338850	338851
Boiler	270236	263163	270236	287975	292844	285621	292844	284996	259292	251919	259292	279380
Juice heating	203052	203050	203052	202786	203067	203064	203067	201990	202983	202981	202983	202989
Clarification	204359	204356	204359	203992	204381	204378	204381	202886	204256	204252	204256	204264
Evaporator	214725	214720	214725	213292	214754	214750	214754	209238	214587	214583	214587	214599
A-Pan	208786	210624	209299	208192	208943	210820	209474	206013	208800	210716	209329	209172
A Crystalliser	206001	206555	206157	205656	206082	206648	206243	204390	205852	206429	206013	205977
C-Pan	206768	208610	207282	206285	206904	208784	207435	204511	206886	208806	207415	207249
C Crystalliser	203958	204515	204114	203723	204016	204585	204178	202861	203911	204492	204072	204028
Centrifuge	212774	217094	213853	211966	213059	217465	214179	208698	212983	217492	214090	213760

Note: Transport capacity was increased by 22 trucks for Scenario 2 and decreased by 25 trucks for Scenario 3.

The reason why the weekly SC capacity is expressed as 60 000 $t.wk^{-1}$, and not 58 000 $t.wk^{-1}$, is because the number of mechanical harvesters required was rounded up to the nearest whole number. The manual cutting capacity was, therefore, increased to match the mechanical harvester capacity for equal comparison of the two harvesting scenarios.

A typical mill in KwaZulu-Natal has the following trend in capacity constriction areas throughout the season:

- fibre C_{min} in the mill front end in early season
- sucrose C_{min} in the A-Pan over midseason
- non-sucrose C_{min} in C-Pan at the end of the season

The seasonal *CU* trends correspond for manual and mechanical harvesting scenarios during average weather conditions. Once enough sugarcane is grown for the mill to run at 100% utilisation, CAPCONN estimates that Komati Mill will have the following potential bottlenecks:

- non-sucrose C_{min} in C-Pan in early season
- sucrose C_{min} in the A-Pan over midseason
- non-sucrose C_{min} in C-Pan at the end of the season

The trends were confirmed during consultation with Komati Mill managers. Possible reasons for the unusual C-Pan bottleneck in the early season at Komati Mill are:

- Preparation and dewatering equipment has been over designed to accommodate the expected future increase in crush rate.
- Billeted sugarcane can be seen to have a higher crush rate capacity, hence this trend may be greater under mechanical harvesting.
- The fibre content in Mpumalanga may be lower than in KwaZulu-Natal. Different varieties are suited to different rainfall and soil types and can have significantly different fibre contents
- The rock and trash removal system significantly lowered trash and therefore fibre levels.

Table 7.2 shows that in the case of manual green sugarcane harvesting the required sugarcane throughput rate is limited by the transport fleet capacity. Were the industry to change to green sugarcane harvesting, the transport fleet capacity would need to be increased. The decrease in transport throughput capacity results from the lower density of green sugarcane with high levels of tops and trash. Under mechanical green sugarcane harvesting the required sugarcane throughput is met although the transport fleet has excess capacity. This is a result of an increase in payload and decrease in turnaround time, which both increase the capacity of the fleet.

The transport fleet capacity was increased by 22 trucks for the green manual scenario and decreased by 25 trucks for the mechanical scenario in order to achieve the same capacity use compared to the current system.

7.1.1 Capacity utilisation in dry weather scenarios

Dry season scenarios were based on average sugarcane quality, hence produce average results while the wet season scenarios represent extreme cases of poor sugarcane quality. The following section discusses the components which are most highly utilised and those under utilised for each of the three scenarios. The cost of loading and transport components are also discussed.

It should be noted that in comparing scenarios, the adjusted scenario input values, discussed in the introduction to Chapter 7, are used as they represent a more realistic system for Scenarios 2 and 3.

The harvest component capacity, for all scenarios under the existing harvest method, equalled C_{min} throughout the season. Harvest units were sourced according to the available seasonal sugarcane mass, hence the amount of sugarcane drives the harvest capacity. Harvest capacity cannot essentially be viewed as C_{min} as it was assumed there will always be sufficient harvest units. Looking at the next highest *CU* for each system provides insight into the actual and possible future capacity constrictors.

For Scenario 1 the SC capacity was constricted next in the transport and mill back end components. The *CU* of these components ranged from 80% to 89%, which showed that the system capacity is possibly over designed for a manually harvested burnt sugarcane system. If the seasonal tons were increased, these components would first form bottlenecks. Of the components which are potential bottlenecks, the most underutilised are loading at 54% and preparation at 65% throughout the season.

For Scenario 2 an addition of 22 trucks raised the transport capacity to handle 60000 $t.wk^{-1}$. The second highest utilisation was in the dewatering mill in early and late season at 89% utilisation, and the transport component at 86% utilisation. During the mid season the transport and A-Pan *CU* are highest at 86% and 85%, respectively. Similarly to the manually cut burnt sugarcane scenario, the most underutilised components are loading at 59% and preparation at 61% throughput the season. The increase in CU_P utilisation from 65% to 70% when moving from Scenario 1 to Scenario 2 is as a result of the higher fibre levels in green sugarcane.

In Scenario 3 the second highest *CU* after transport (which is at 88%), is the boiler at 87% throughout the season and the A-Pan at 87% during the midseason. Preparation was the most unutilised component, at 54% throughout the season. The decrease in preparation *CU* from 65% to 54% when moving from Scenario 1 to Scenario 3 is as a result of the higher throughput capacity when crushing billets.

Loading and transport utilisations are seen to be significantly different in the existing system at 54% and 86%, respectively. The reason for the large difference in the two utilisations is believed to be related to the cost of equipment. CAPCONN estimates the cost of transport constitutes 30% of the total production cost of sugar, from growing to milling, which is over seven times that of loading. Since loaders are cheaper, it is logical to overcapitalise on loaders to reduce truck delays. CAPCONN estimates that transport is 14% overcapitalised. However, a more detailed investigation would be required to determine whether this excess capacity is needed as a buffer. Decreasing turnaround time (through scheduling software) would increase the $t.hr^{-1}$ throughput of each truck and hence increase fleet efficiency.

7.1.2 Process performance and cost under dry weather scenarios

Tables 7.2 and 7.5 show the general operational outputs for the unadjusted and adjusted scenarios, respectively. Scenario 1 was compared with the adjusted versions of Scenarios 2 and 3. The major production differences between these scenarios are discussed followed by a discussion of trends within each scenario.

The most significant observation from Tables 7.3 and 7.6 is that the production cost ($R.t^{-1}$ sugar) for Scenario 2 is 10% higher compared to Scenario 1. This trend is as a result of sugarcane quality and cost levels. Inverse trends in cost and recovery patterns result in the increasing $R.t^{-1}$ cost from Scenario 1 to 3. The quality and cost trends are further discussed below.

The sugarcane quality parameters impacting on recovery are soil (*A*) and trash (*TSH*). Higher soil and trash levels in Scenarios 2 and 3 are shown in the mass of sugarcane milled in Table 5.4. The difference in the mass of sugarcane is largely due to different soil and trash compositions.

Table 5.4 Comparison of seasonal SC milled mass during the early season

	Scenario 1 Manual cut burnt sugarcane	Scenario 2 Manual cut green sugarcane	Scenario 3 Mechanically cut green sugarcane
Field mass (Mt)	2.80	2.80	2.80
Seasonal mass milled (Mt)	2.08	2.18	2.16

For each ton of sugarcane there is effectively less sucrose in Scenarios 2 and 3, Scenario 2 having the highest *F* levels followed by Scenario 3. *F* has a compounding effect on reducing sugar production rate, not only occupying a mass component, but it also increases losses to bagasse. The third effect of *F* is in purity reduction, which has not been included in CAPCONN. The combined *E %* and *X %* is highest for Scenario 1 and lowest for Scenario 3, which is explained by the *F*, *A* and *NS* levels. *X %* is highest for manually harvested green sugarcane (Scenario 2) and then mechanically harvested green sugarcane (Scenario 3) showing the *NS* levels are highest in Scenario 1 and lowest in Scenario 2. The sugar recovery pattern ($t.hr^{-1}$) is inversely proportional to the total cost pattern. Scenario 3 has a 20% higher production cost. Scenario 3 has the lowest *FC*, but significantly higher *VC*, and the stock cost is almost 1/3 of that of Scenario 1 and 2. This is a result of the lower HTCD. Soil milling costs are highest under Scenario 3.

After comparing quality, throughput and cost trends in each scenario, some operational trends within each scenario are now discussed. In all scenarios the highest E % occurs in mid season, when *F* levels are lowest. The equal outputs of E % in early and late season corresponds to the equal *F* levels shown in Table 5.1 above, and equal *A* levels which is reflected by the equal early and late season soil maintenance cost in Table 7.2.

CAPCONN provided insight into the costs associated with each component of the SC. The effect of adding trucks in Scenario 2 and reducing trucks in Scenario 3 can be seen with the 13% increase and 7% decrease in transport costs respectively. An investigation of the diagnostics sheet showed the ratio of mill front end to back end costs are 83% to 17 % which corresponds to the 80% to 20% relationship mentioned in section 5.3.4.3.

7.2 Capacity Utilisation, Processing and Costs Under Wet Weather Scenarios

As mentioned in the introduction of this chapter, wet weather scenarios represent extreme sugarcane quality situations.

Tables 7.1 and 7.4 show the capacity of Scenario 1 was not affected in wet periods, and that Scenario 2 and 3 are limited by E% (fibre levels) and boiler (soil levels) capacity. This is a result of the increase in trash and soil levels which is described in Section 3.1.

Table 7.2 shows a 15% increase in mill maintenance costs in Scenario 3 as a result of the increase in soil levels. In all three scenarios E % decreased with higher soil and trash levels. X% remained constant or increased with lower non-sucrose levels, as the sugarcane had significant levels of soil and trash which contain no non-sucrose. This would not occur in reality as during wet weather exhaustion levels can be as low as half of the average X% levels (ESR, 2005). Higher fibre and soil content and lower E% reduced the sugar recovery in all scenarios. The increase in VC and decrease in sugar production rate resulted in a significant increase in production costs, up to 50% in Scenario 3.

An important aspect of mechanical harvesting is that the harvester cannot operate in wet fields and does not effectively cut wet sugarcane. Hence, under a large mechanical harvesting fleet the industry may be forced to shut down during periods of high rainfall. A general rule is that for every millimetre of rain, one hour of harvest time is lost (*pers. comm.*[29]). The impact of weather conditions on harvesting capacity is not included as it is desirable to compare scenarios under the same harvest throughput rate. This issue is further discussed in the recommendations for future research section.

7.3 Case Study Conclusions

CAPCONN provided insight into SC operations at Komati Mill on a strategic and tactical planning level, allowing the SC to be viewed as a single business entity. The output trends correspond to those described by TSB employees after consultation. The model framework provided insight into the current system and the implications of practicing manual and mechanical green sugarcane harvesting were highlighted. The integrated impacts of sugarcane quality on the system were demonstrated and the implications could be assessed in terms of throughput impacts and production cost. CAPCONN estimated that Komati Mill was between 11% and 14% overcapitalised throughout the season, viewed on a strategic planning level. This corresponded to reports that the mill is designed for a 2.6 million ton season, but to date had averaged 2.2 million tons per season.

One of the most significant observations is that the $R.t^{-1}$ is lowest for current system of burned manual harvesting and highest for green mechanical harvesting. This is a result of an increasing trend in total production cost and decreasing trend in recovery when moving from burned manual to green mechanical harvesting. Mechanical harvesting of green sugarcane is estimated to increase production cost by 20% whereas manually harvesting green sugarcane increases production cost by10% throughout the season.

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[29] S. Davis, Mill Process Engineer, SMRI, Durban, South Africa, January 2006

Scenarios 2 and 3 showed significant impacts on transport capacity. When the system was changed from burnt to green sugarcane harvesting, the transport capacity was reduced by 34% as a result of the density decrease in sugarcane. Likewise, under mechanical harvesting, truck utilisation increased by 39% as a result of greater payload and quicker turnaround time. This decrease in transport costs may compensate for the increase in harvesting costs. Mechanical harvesting is seen to involve higher risks in wet weather conditions. High soil and trash levels result in high production costs and low sugar yields. Under green whole stalk harvesting, high fibre levels may limit mill throughput during wet periods.

As quoted from a mill engineer, sugar milling is no exact science. Hence mill processes have been conservatively modelled. It is believed that the effect of trash and soil on milling processes has been handled conservatively.

8 DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

8.1 Discussion and Conclusions

Integrated modelling of the sugarcane supply chain was investigated through the development and demonstration of the CAPCONN model framework. The suitability of computer models for such applications was demonstrated, facilitating the capture, visualisation and manipulation of a complicated system. Furthermore, the effectiveness of integrated modelling was highlighted, capturing the cascading intra-component impacts of a relatively non-integrated system.

The literature review provided insight into the available modelling techniques and their application in industry. Since none of the models reviewed were believed to be suitable for use in this project, and no techniques were particularly applicable, CAPCONN was derived from first principles using the concepts of capacity and constriction. The algorithms used in CAPCONN were based on pipe flow dynamics, in which conveyance is restricted to the lowest throughput capacity in the pipeline, analogous to a chain being as strong as its weakest link. The variable relationships within and between components, especially in the mill, are generally complicated and were often difficult to model. It was decided to base the modelling algorithms only on the significant variables, which are the twenty percent of all the supply chain variables that control approximately eighty percent of supply chain process operation. CAPCONN was specifically configured to assess the impact of mechanical harvesting on the supply chain. Hence, mill process performances were modelled as functions of trash %, soil % and non-sucrose %, which are the variables that are sensitive to the harvesting practice used. Furthermore these variables have a significant impact on mill process operation.

CAPCONN calculates the capacity of each component in the supply chain and then identifies the lowest throughput capacity. The cost of operating each component at this throughput capacity is then calculated. Sugarcane quality, operational and naturally occurring (e.g. sucrose deterioration) processes are used to determine capacity and costing. In general, a significant amount of inputs are required, which are obtainable through measurement, from the literature, consultation and, where necessary, theoretically assumed. Prior to the case study, CAPCONN was evaluated through a variable assessment and a sensitivity analysis. The results showed that CAPCONN's output trends are reliable, though the magnitude of the trends should be viewed with caution, which is expected since the inputs and algorithms used were often simplified or assumed. The reliability of the output trends confirms that the model framework is functional.

CAPCONN was demonstrated through a mechanisation study at Komati Mill. The integrated impacts of different harvesting methods were assessed. CAPCONN confirmed that the supply chain was overcapitalised. It was estimated that the total production cost would rise by 20% should the harvest practice move from burned manual harvesting to green mechanical harvesting. The transport fleet size was reduced by 40% to maintain the existing truck utilisation. The utilisation increase is a result of increased payload and lower turnaround time, which may compensate for the increase in harvesting costs. Under manual harvesting of green sugarcane, the total production cost increased by 10% and it was necessary to increase transport fleet size by 34% to achieve the current truck utilisation value. Here, transport capacity decreased due to a decrease in produce density. These trends were greater during wet weather, especially under mechanical harvesting, resulting in a reduction of supply chain capacity below the required weekly capacity. The problems associated with wet weather caution against a fully mechanised harvesting strategy.

This project has demonstrated that there is sufficient information and expertise in the South African sugar industry to develop an integrated supply chain model. It has shown that an integrated modelling approach provides improved insight and problem solving capabilities. Revisions to modelling inputs and algorithms would transform the model framework into a full scale model, which may in time become a valuable tool for the sugar industry.

8.2 Recommendations for Future Research

CAPCONN applications

The CAPCONN model framework has been developed in this study. It is envisioned that the model framework will be developed into a model for use by the South African sugar industry. The first steps in transforming the framework into a model are to further develop all modelling relationships used, and to obtain accurate input data. The elements of the CAPCONN model framework believed to have the highest priority of adaptation are outlined in the modelling adaptations section below. It is intended for these to serve as a starting point for the transformation of the model framework into a model.

CAPCONN was configured to represent one week's supply of sugarcane from field to mill back end. The next step in the development of a CAPCONN model would be to replicate this to resent a full milling season. Different supply lines can be represented by different cohorts that converge at the mill. This will enable CAPCONN to be used as a strategic planning tool. Problems, such as optimising the length of milling season (LOMS), can be addressed by selecting the number of milling weeks by minimising the total seasonal cost. Other problems such as optimising variety selection and mill location can be optimised. It should be noted that such optimisation capabilities would run parallel to the existing CAPCONN simulation model framework.

CAPCONN can be used as a capacity planning tool. The optimal supply capacity distribution can be determined by selecting the capacity in each component subject to minimising production cost. The cost of increasing or decreasing the capacity of a component can be represented by the dual price ($R.t^{-1}.hr^{-1}$).

CAPCONN serves as a tool to identify problem areas in the supply chain. The cost for the mill to purchase sugarcane is currently 80% of the total milling cost. Therefore in order to reduce production cost of sugar the majority of focus needs to be on field to mill operations (*pers. comm.*[30]).

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[30] S. Davis, Mill Process Engineer, SMRI, Durban, South Africa, January 2006

Modelling adaptations

A number of simplifications have been made in the modelling of supply chain components. The following list represents the improvements that should be made to the CAPCONN model framework as part of an ongoing research and development process.

1. The mechanical harvesting scenario assumed that trucks are loaded infield. Mechanical harvesting operations may include tractor-trailer units which are loaded during harvesting and transfer the produce to trucks alongside the field.
2. Field inaccessibility and compaction are significant problems associated with mechanical harvesting, especially during periods of rain. This should be accounted for in the harvesting $hrs.wk^{-1}$.
3. Agronomic problems associated with converting to a mechanised harvesting system are outlined by Meyer *et al.* (2005), and should be considered.
4. The mass loss of the sugarcane plant when burnt was not accounted for and may be significant when comparing burnt and green harvesting scenarios.
5. Sugarcane deterioration has been modelled. The use of more advanced deterioration equations for each type of harvest method would improve the accuracy of deterioration determination. Furthermore in the conversion of sucrose to non-sucrose, the non-sucrose must be increased proportionally to the amount of sucrose vs. non-sucrose and not just by the % deterioration as there is more sucrose than non-sucrose.
6. Theoretical coefficients have been used for the rock and trash removal system which must be replaced by tested values.
7. Mill extraction and exhaustion processes have been highly simplified and should be improved.
8. The Vucov Equation discussed in Section 4.3.1 should be used to determine mill inversion losses.
9. Simplified FC and VC figures have been used in all components and theoretical values have been used for mill processes. These values need to be improved in further development stages of the model.
10. The supply chain costing does not include the opportunity cost of land which may be significant when assessing whether to convert to other activities (Cock *et al.*, 2000). The agronomic cost used must be added to the VC in order to

calculate the TC ($R.t^{-1}$) and the CAPCONN value needs to be updated, being approximately one fifth of the industry value of 100 $R.t^{-1}$ (*pers. comm.*[31]).

11. The weekly time step significantly simplifies the modelling detail of the supply chain. Were the model adapted to handle smaller time steps, through sub-models within each component, the component processing time and delay per component cycle could be determined. A knowledge of component cycle time (e.g. vehicle turnaround time) and the sugarcane capacity per cycle (e.g. vehicles × ρ) would be required to model smaller time steps. Knowing the component processing time and the delay per component cycle would be useful in finding the time taken for each unit of produce to travel through the supply chain. This time would be used to calculate the HTCD and SC.

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10 APPENDIX

2005 SMRI data for Komati Mill

Week	Fibre % sugarcane	Sucrose % sugarcane	Non-sucrose % sugarcane	Ash % sugarcane	Extraction %	Overall recovery or exhaustion %	Sugar price ($R.ton^{-1}$)
1	12.87	11.80	3.01	0.45	98.38	81.73	
2	12.14	12.46	2.96	0.46	98.32	81.94	
3	12.51	12.98	2.88	0.59	98.16	85.69	2175.49
4	12.69	13.03	2.89	0.54	98.29	86.12	2175.49
5	12.61	12.98	2.86	0.51	98.09	87.64	2175.49
6	12.76	13.96	2.63	0.55	98.13	87.58	2175.49
7	12.48	13.34	3.02	0.48	98.24	85.75	2175.49
8	12.76	13.99	2.84	0.50	98.24	88.28	2117.47
9	12.60	13.79	3.07	0.53	98.04	86.51	2117.47
10	13.13	14.28	2.76	0.50	98.50	87.53	2117.47
11	13.09	14.00	2.69	0.48	98.20	87.78	2117.47
12	13.94	14.35	2.42	0.54	98.29	88.90	2133.00
13	13.40	14.43	2.41	0.56	98.24	88.68	2133.00
14	12.91	14.22	2.69	0.45	98.13	87.62	2133.00
15	12.94	14.50	2.55	0.57	97.97	88.25	2133.00
16	13.49	14.60	2.59	0.54	98.25	88.97	2188.31
17	13.65	14.50	2.66	0.51	97.94	88.18	2188.31
18	13.69	14.72	2.84	0.50	98.27	88.86	2188.31
19	13.94	14.92	2.95	0.54	98.40	88.74	2188.31
20	13.74	15.13	2.99	0.38	98.45	86.38	2188.31
21	13.78	14.99	3.00	0.32	98.44	88.42	2211.99
22	13.68	15.52	2.91	0.38	98.37	88.43	2211.99
23	13.54	15.28	3.30	0.21	98.20	87.20	2211.99
24	13.49	14.94	3.55		98.44	86.19	2211.99
25	13.68	14.79	3.59	0.43	98.22	84.95	2214.11
26	13.95	14.81	3.68	0.48	98.43	85.38	2214.11
27	14.13	14.87	3.69	0.48	98.42	83.85	2214.11
28	14.07	15.11	3.34	0.36	98.36	85.71	2214.11
29	14.97	13.79	3.07	0.50	97.95	84.55	2214.11
30	14.79	13.90	3.20	0.50	98.09	83.26	2226.82
31	15.16	12.72	3.35	0.50	98.10	83.75	2226.82
32	15.78	12.12	3.03	0.52	97.66	83.44	2226.82
33	15.35	11.81	2.87	0.56	98.11	85.27	2226.82
34	14.72	12.43	2.81	0.38	98.17	84.33	2241.18
35	15.97	11.60	2.95	0.36	97.92		2241.18
Max	15.97	15.52	3.69	0.59	98.50	88.97	2241.18
Min	12.14	11.60	2.41	0.21	97.66	81.73	2241.18