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Modelling sugarcane supply consistency at a sugar mill

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ABSTRACT

The sugarcane supply chain has been defined as a generally inclusive agri-industrial system that aims to grow, harvest, transport and process sugarcane from the field to the mill. Based on a literature search, there has not been a study on predictive sugarcane supply consistency at a mill-scale, which has the ability to play the mill crush capacity. The aim of this research was to develop, calibrate and verify a semi-mechanistic model, in order to identify the impacts of different factors to the sugar mill crushing operations. The work was carried out at the Eston Mill in KwaZulu-Natal, South Africa, but could be applied to any sugarcane milling area. The model involved the calibration of parameters for mill maintenance and operational stops, rainfall events and days in the week when slow crush rates occurred. The modelling approach confirmed that fibre loading, mill maintenance stops and breakdowns, as well as rainfall and weekday inconsistencies all have an impact on daily crush rates at the Eston Mill. The model captured approximately 64% of the variation observed in daily crush rates. The model can be utilized to critically evaluate different sugarcane milling areas and could potentially make significant contributions to cane supply management and milling operations. The model could also be used to quantify the magnitude of different disruption factors in a milling area.

1. Introduction

The sugarcane supply chain has been defined as a generally inclusive agri-industrial system that aims to grow, harvest, transport and process sugarcane from the field to the mill (Gigler et al., 2002; Gaucher et al., 2004; Amu et al., 2013). Before any significant improvements can be made, the sugarcane supply chain must be researched more holistically than in the past, while considering various concurrent issues (Le Gal et al., 2004; Bezuidenhout and Baier, 2011; Thorburn et al., 2011). There are currently limited techniques available in the sugar industry, to quantify and predict the impacts of a decision, such as the harvest date of a cane field (Higgins et al., 2007; Lejars et al., 2008; Amu et al., 2013). Furthermore, Bezuidenhout et al. (2012a) argued that a "one-size-fits-all" approach to optimising systems is unlikely to be a successful solution in the sugar industry. This is due to each mill being unique because of its history and the various biophysical issues on the ground, at different times (Bezuidenhout et al., 2013).

Kadwa and Bezuidenhout (2013) identified various causes of sugarcane supply uncertainties and broadly categorised them into three groups, namely, cane quality, quantity and processing uncertainties. There are several types of uncertainties that occur in supply chains (Tachizawa and Thomsen, 2007; Pitty et al., 2008) and this makes it difficult for the sugarcane industry to optimise productivity. Uncertainties create risk and may decrease profitability for the parties involved in the supply chain, by negatively impacting on mill operations and capacities (Le Gal et al., 2008, 2009; Kadwa and Bezuidenhout, 2013).

Due to the various uncertainties, there are different strategies or methods, which have been proposed to improve sugarcane supply chains. These strategies have to be flexible, to allow for ever-changing uncertainties (Gaucher et al., 2003; Chen and Paulraj, 2004; Tachizawa and Thomsen, 2007). The strategies that have been used include, amongst others, (a) increasing communication and collaboration between the parties in the supply chain (Gaucher et al., 2004; Lejars et al., 2008; Bezuidenhout et al., 2012b; Sanjika et al., 2012), (b) optimising the length of the milling season (Moor and Wynne, 2001; Wynne and Groom, 2003; Stutterheim et al., 2009), (c) introducing the correct sugar payment system (Wynne, 2001; Todd and Forber, 2005; Lejars et al., 2010), (d) stockpiling (Higgins et al., 2006; Bezuidenhout, 2010; Boote et al., 2013), rearranging harvest scheduling (Muchow et al., 2000; Higgins and Muchow, 2003; Higgins, 2006; Le Gal et al., 2008; Stray et al., 2010, 2012), and (e) new co-ordinated delivery allocation rules (Higgins et al., 2004; Giles et al., 2005; Higgins and Laredo, 2006; Milan et al., 2006; Le Gal et al., 2009). Kadwa

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and Bezuidenhout (2013) devised a conservative, yet simple and well-structured analytical process to analyse sugarcane seasons. However, the approach can only be used when analysing historical data. Based on a literature search, there has not been a study that focused specifically on modelling sugarcane supply consistencies at a mill-scale and extrapolating it in a way that has the ability to operationally predict future mill crush capacities.

The aim of this research was to develop, calibrate and verify a semi-mechanistic model, in order to identify and quantify the impacts of disruptions to the sugar mill crushing operations. The work was carried out at the Eston Mill in KwaZulu-Natal, South Africa.

2. Model development, calibration and verification

The Eston Mill (29°87′S 30°53′E), which was established in 1994, is the newest in the KwaZulu-Natal sugar belt. The average annual rainfall in the region ranges from 800 mm to 900 mm and the average temperature is approximately 18–19 °C. 80% of the rainfall occurs between October and February, which results in the milling season spanning from mid-March to the end October/November each year. The Eston area is situated at a relatively high altitude (400–900 m above sea level). The area produces an average cane yield of 80 t/ha. The mill crushes an average of ~1.2 million t of sugarcane annually (see Table 1), which results in approximately 130,000 t of sugar and 50,000 t of molasses (Lumsden et al., 1998, 2000; Lyne et al., 2005; Kadwa et al., 2012; Bezuidenhout et al., 2013; Kadwa and Bezuidenhout, 2013).

The cane supply consistency model that is described in the next section was developed and calibrated using four milling seasons (2004, 2005, 2011, and 2012), whilst five other seasons (2006–2010) were reserved for verification purposes. Utilizing the 2004, 2005, 2011 and 2012 seasons for model development and calibration maximised the model's predictive capacity. Table 1 summarises the different seasons. The analyses were based on a daily time step, which included sugarcane crush records, in tons per day ($t\,d^{-1}$); mill stops and breakdowns, in minutes per day ($min\,d^{-1}$); and rainfall events, in millimetres per day ($mm\,d^{-1}$).

2.1. Model development

The first step of model development involved the quantification of the mill's capacity for a given day. Sugarcane mills have several sequential industrial processes, such as fibre and juice separation, evaporation, energy regeneration, crystallization and molasses separation. The percentage of fibre in sugarcane at the time of mill crushing (fibre % cane), was identified as a key limiting factor at the Eston Mill (Bezuidenhout et al., 2013). The diffuser, where soluble sugars are extracted from insoluble fibres, tends to flood when cane with high levels of fibre is processed, which results in a decreased daily mill crushing capacity. For this reason the mill may need to run at a slow processing rate, even if other processes are underutilized. In the model, fibre loading was used to constrain the maximum potential daily crush rate (PDCR). The PDCR is the quantity of sugarcane that possibly would have been crushed for the day, after considering fibre loading, before the consideration of other mill disruptions. Fig. 1 illustrates the historic relationship between fibre % cane values and the actual daily crush rates (ADCR), for the 2004, 2005, 2011 and 2012 seasons. The solid line depicts the PDCR. 98% of all data points are situated below the solid line. The solid line indicates a strong negative trend between fibre % cane and the maximum attainable crush rate. Increased levels of fibre % cane, therefore, results in a decreased PDCR.

A crush gap was determined by subtracting the ADCR from the PDCR, as demonstrated for a single point in Fig. 1. The crush gap could be due to numerous factors, such as rainfall, mechanical breakdowns, maintenance stops, as well as pay-weekends that often cause cutter absenteeism. These factors will differ from mill to mill and needs to be modelled appropriately.

In this milling area, mill breakdowns and maintenance stops were the first disruption factors to be considered in the Eston model. Mill stops that were due to rain and cutter absenteeism were excluded from this part of the model. However, other indirect mill breakdowns due to rain usually occur frequently towards the end of the milling season in South Africa. It was assumed that stops and breakdowns have a pro rata impact on daily crush rates. In other words, for each breakdown hour, a 4.17% reduction in the daily crush rate would occur. This assumption was verified by regression analysis against the actual crush rate data, after the mill's records concerning mill stops were carefully analysed. Eq. (1) was used to calculate the impacts of breakdowns and maintenance stops on daily crush rates.

$$\mathrm{BD}_i = \mathrm{BDM}_i \div (60 \times 24) \times \mathrm{PDCR}_i \quad (1)$$

where

BD_i is the reduction of daily crush rate in tons on day i, due to breakdowns and maintenance stops,

BDM_i is the total duration of breakdowns and maintenance stops for day i (in minutes), and

PDCR_i is the fibre loading estimated achievable daily crush capacity for day i, (see Fig. 1).

Rainfall was the second most influential disruption factor considered to increase the crush gap. Rainfall can disrupt cane burning prior to harvest, but also causes in-field mobility problems, which make it difficult for equipment to move large quantities of cane out of the fields. This leads to decreased cane supply to the mill. In addition, the wet conditions will cause loose leaves and soil particles to adhere to the sugarcane, which will increase the fibre loading. It is, therefore, likely that some of the impacts of rainfall are already modelled by the fibre loading factor in Fig. 1.

After consulting with local supply chain stakeholders, it was assumed that the impacts of rainfall on mill crushing can last for a maximum period of five days. The first few days after a rainfall event will be impacted more severely and over a period of five days, operations could be expected to slowly recover back to normal. For example, a rainfall event will disrupt cane supply to the mill more significantly on the first two days, than on the fourth day, as the fields become more accessible. For this reason, the impacts of the first five days since a rainfall event were weighted according to their response in crush rate recovery, as formulated in Eq. (2). The mean rainfall from the six climatic zones in the Eston region enabled the weighted impacts of each day to be calibrated, based on the disruptions in the mill crush rates after a rainfall event.

$$R_i = \sum_{j=i-4}^{i} w_j (c + d\overline{P}_i) \quad (2)$$

where

R_i is the fraction of the PDCR reduced by rainfall for day i,

w_j is the weight for each of the five days after a rain event [$j = i - 4, \ldots, i$] ($\sum w_j = 1$),

c is the offset fraction (%),

d is the slope of the function ($\% \, mm^{-1}$) and

$\overline{P}_i$ is the mean rainfall, in mm, that occurred across six climatic zones in the Eston region on any day P.

The last variable considered for the model, at Eston, involved the estimation of the impacts of weekday inconsistencies. Worldwide, labour intensive farming operations follow weekly patterns.