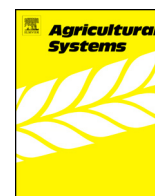




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When do I want to know and why? Different demands on sugarcane yield predictions

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ABSTRACT

The production planning processes of sugarcane mills require quantitative information to support decisions on sugarcane yield and the effects of decisions made during planning. An exploratory study was conducted at a sugarcane mill with the goals of identifying the main decisions influenced by the prospects of future yield and of evaluating the manner in which those forecasts affect planning. Key decisions and their characteristics were identified based on a series of interviews and activity monitoring. These decisions are presented and discussed in relation to various solutions proposed by the scientific community for planning, as well as within the concept of Advanced Planning Systems. The yield forecasts used to inform budgeting and harvesting plans are of critical importance because actions taken based on those forecasts affect the entire value chain, highlighting the need for a decision-making framework that assess the effects of decisions on subsequent processes. Advanced Planning Systems design to the sugar value chain should incorporate the use of yield forecasts for production and must address the uncertainties throughout the entire system. These improvements can enhance the performances of Advanced Planning Systems by producing an integrated planning approach that is based on a comprehensive assessment of the sugar value chain.

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1. Introduction

Yield forecasts are a key component used for setting goals, evaluating alternatives, and specifying management plans during the crop production planning process. Given the long growth cycle of sugarcane, yield forecasts are developed well in advance, and time frames of one year or longer are not uncommon. Also as a consequence of the long growth cycle, there are several opportunities to revise forecasts if there is an increase in available information that can be used to produce better yield forecasts. As the harvest approaches, forecasts are no longer revised, and it becomes possible to estimate yields based on visual field surveys or on field sampling, the latter of which is better suited for providing estimates of yield. When there is a longer period between the yield prediction and the harvest (e.g., 6 months or longer), a yield estimate is more appropriately called a yield forecast because several future events, such as future weather events or the emergence of an adverse plant-health conditions, could still affect the yield. Based on this adopted differentiation between an estimate and a forecast, the term forecast is used in this report when referring to the prediction of future results.

Notably, a common practice of the sugarcane sector is the yield estimation by specialists. Sugarcane-production specialists are capable of estimating yield based on visual assessments or of generating yield forecasts based on their knowledge of the region's history, the cultivar performance, the land characteristics, the typical weather, and the occurrences of pests and diseases. In a broader context, yield forecasts are the basis of the sugarcane production planning process, whereas revised forecasts allow for the adjustment of management practices. While yield forecasts are important for sugarcane mills, the quantity of sugar accumulated in the stems is also critical information because it indicates the potential for industrial production in terms of sugar and/or ethanol.

The decisions that can benefit from the use of forecasts and modeling, as described by several authors, vary in scale, are required at various times in advance of harvest, and are performed by multiple distinct decision-makers (Ahumada and Villalobos, 2009; Everingham et al., 2002; Meinke and Stone, 2005), illustrating the complexity of the sugar value chain, as reported by, e.g., Higgins et al. (2007). Ahumada and Villalobos (2009) have reviewed various decision-making support systems for agricultural value chains in terms of the organizational level (operational, tactical or strategic) of decision-making and in terms of the functional process affected (cultivation, harvest, distribution, or storage), while also differentiating the systems in terms of the type of model used (stochastic or deterministic). Meinke and Stone (2005) provided examples of decisions that can benefit from the use of climate forecasts, varying from decisions to support internal harvest logistics

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to those influencing land-use policies implemented at varying frequencies (intra-harvest to decadal) and varying time scales (months to decades); that study also highlighted the use of models to elaborate yield forecasts. The relationship between the time of decision-making and the time window for decision-making determines which meteorological data are available and which should be forecast. Everingham et al. (2002) used climate forecasts to make decisions affecting the sugar value chain and reported a list of key decisions that were influenced by seasonal climate forecasts. The authors divided the value chain among cane growing, harvesting and transportation, milling and production, and sales. They defined key industry decisions and used the climate forecast to improve decision-making for 4 aspects of these identified processes, including (a) yield forecasting and its effect on sugar sales in future markets, (b) the use of climate forecasting to make decisions regarding irrigation management, (c) determinations of yield at the beginning and end of harvest, and (d) harvesting practices.

When the value-chain decision-making process is analyzed, the impacts of decisions on subsequent echelons can also be analyzed, and the use of forecasts and modeling can improve the decision-making process in a context beyond solely agricultural production, *per se*. Ahumada and Villalobos (2009) characterized the agricultural value chain as consisting of production, harvest, storage, and distribution. Higgins et al. (2007) added the processes related to sugarcane mills, i.e., milling and sugar production, sugar transportation and storage, and the production of other sugarcane-based products (e.g., ethanol and biomass electricity) to the value chain because the chain is agro-industrial in nature. In addition, groups that control more than one mill can benefit from a decision-making process that considers several of the group's units. Higgins et al. (2007) considered the existence of several agents along the sugar value chain to be one of the challenges that is hindering the adoption of a joint decision-making framework. The sugar value chain, based on the divisions of Higgins et al. (2007) and Ahumada and Villalobos (2009), is depicted in Fig. 1. While the reviewed literature and the considerations for the present study refer to the sugar value chain, the results can be extrapolated to other products of the sugarcane complex (e.g., ethanol and electricity).

Given the importance of sugarcane yield forecasts for supporting several decisions made within the agro-industrial sugar value chain and given the ability to revise yield forecasts during the crop development phase, the objectives of this study were (1) to identify the various decision-making and planning processes that are supported by yield forecasts, (2) to assess the manner in which yield information is used within those contexts and the characteristics of its use, and (3) to evaluate the structures of yield models and planning models in relation to the concept of Advanced Planning Systems (APS) and identify any gaps that exist between the models and the APS concept. The results of this study will improve the understanding of the decision-making processes required by the sugar value chain, expanding decision-making beyond processes based solely on climate forecasts by including decisions that could potentially benefit from yield and planning models. We also establish the main characteristics of such decisions, according to the framework of Meinke and Stone (2005).

2. Yield and planning models to support the sugarcane complex

Danese and Kalchschmidt (2011) investigated the effects of forecasts on operational performance and determined that, for manufacturing companies, the adoption of a structured forecasting process



Fig. 1. A simplified sugar value chain for the sugarcane complex.

oriented towards decision-making has a direct, positive impact on the costs and performance of deliverables. Surprisingly, the results of that study indicate that the impact of a given forecast on operational performance is not mediated by forecasting error, meaning that a smaller error does not necessarily result in better company performance. In addition, their analysis revealed that the adoption of yield-forecasting techniques does not necessarily reduce the forecasting error. According to the authors, the best operational performance is associated with the variable “information collection from different sources to elaborate forecasts”, which is related to the acquisition of information from multiple sources, such as both suppliers and consumers, to establish the demand forecast and with the variable “role of forecasting in decision-making”, which is related to the extent to which a given forecast is used within multiple contexts by the company. Their variable “use of forecast techniques” was also correlated with better operational performance, not by producing forecasts with smaller error but by limiting the potential effects of judgment biases on forecasts and by providing a single forecast for multiple contexts, helping companies to “align” their planning. The authors emphasized that forecasts should be accurate, be available at the right time, and be readily adoptable to support decision-making according to management needs.

Higgins et al. (2007) noted that the main difference between manufacturing value chains and agricultural value chains is the greater variability of the production system involved. The authors refer to climatic and biophysical variabilities/uncertainties as the main factors contributing to this variability. The production systems of manufacturing chains are more predictable and require demand forecasting, whereas the interactions among controlled and uncontrolled factors in agricultural systems necessitate the use of production (yield) forecasts. For the sugar value chain in the Australian context, the aforementioned authors also highlight the involvement of several decision-making agents and varying scales of decision-making processes, from decisions for individual plots to those affecting an entire mill. The presence of multiple agents in the value chain has been highlighted in Australia by Jiao et al. (2005), in South Africa by Le Gal et al. (2009), and in Thailand by Piewthongngam et al. (2009). In contrast, there is only a single production agent for the conditions described for Venezuela by Grunow et al. (2007) and for Brazil by Jena and Poggi (2013).

The yield forecast can be estimated by several methods depending on the available data. One type of yield forecasting is based on growth models, which, coupled with information on crop handling and weather forecasts, can describe plant growth and can be used to generate yield forecasts. Lisson et al. (2005) refer to APSIM-Sugarcane and Canegro as the two main sugarcane simulation models in use worldwide. This type of model has been used in South Africa and Australia with the goal of forecasting the regional yield for the approaching harvest (Bezuidenhout and Singels, 2007a; Everingham et al., 2002). To bypass the information demands for these applications, Everingham et al. (2009) proposed the combined use of the results of several models (an ensemble) with varying modeling conditions to perform the regional yield forecasting in Australia. Another strategy is to group similar areas into homogeneous blocks to decrease the number of growth simulations that must be performed (Bezuidenhout and Singels, 2007a; Le Gal et al., 2009).

An alternative to the use of growth models is the use of an empirical model, which searches for relationships among crop characteristics and climate conditions to determine the final yield. Meinke and Stone (2005), while discussing modeling approaches for yield forecasting, presented both growth and empirical models as tools to study both climate change and climate variability, defining a climate change as a long-term change and climate variability as the intrinsic climate variation.

One direct consequence of the choice of any modeling strategy is the information required, as well as when this information will

be available in relation to the timing of the decision-making or planning process. Growth models can describe the entire crop cycle. Hence, APSIM-Sugarcane and DSSAT/Canegro are components of whole-farm system simulators that can be viewed as highly comprehensive tools. For more information about APSIM and DSSAT, readers are referred to Keating et al. (2003) and Jones et al. (2003). These models require information regarding boundary conditions (e.g., soil, fertilization, and management), weather, and parameters regarding plant growth, which are obtained from calibrated growth curves. Empirical models will require any information used in their creation and can also incorporate information on plant development, such as variables indirectly measured by remote sensing. An example of this type of application was presented by Bégué et al. (2010), who used the remotely sensed NDVI to estimate field yields and obtained the best results when using the NDVI from two months before harvesting. Another possibility is the incorporation of meteorological variables, as described by Rudorff and Batista (1990). Brüggemann et al. (2001) developed empirical models with variables that could be determined six months before harvest to enable the model to be used for planning, and the model that included all of the available information exhibited the best performance. While Brüggemann et al. (2001) explicitly demonstrated how incremental information contributes to reducing error, the inclusion of remotely sensed attributes in models is an obvious example of information that can only be measured and incorporated late in the growth cycle.

As the season progresses, new weather forecasts and the weather conditions that have already occurred can be included in yield simulations, and their inclusion is expected to decrease the forecasting error (Everingham et al., 2002; Hoogenboom, 2000). For empirical models, in addition to climate and crop management information, remote-sensing data can be used to add further information into the yield forecast. Remote-sensing sources include data obtained from satellite sensors, aerial photographs, or terrestrial sensors, which can infer properties such as the leaf-area index (LAI), water stress, nutrient deficiency, plant health, and plant biomass of the crop via the measurement of surface radiometric responses (Abdel-Rahman and Ahmed, 2008). These data can be used to generate models for the spatial scales at which they are available.

In addition to supporting decision-making, yield forecasts can also be included in optimization models for agricultural systems. The existing model applications for sugarcane include models to support the crop plan (Grunow et al., 2007; Piewthongngam et al., 2009), harvesting plan (Grunow et al., 2007; Higgins, 2002; Jena and Poggi, 2013; Jiao et al., 2005; Le Gal et al., 2009), and harvesting schedule (Grunow et al., 2007; Jena and Poggi, 2013; Le Gal et al., 2009). A good crop plan optimizes the delivery of raw material with the highest quantity of available sugar for milling, according to production considerations and mill capacity. The quantity of sugarcane delivered should be such that the mill can operate continuously during the milling season and can, according to the milling capacity, minimize sugarcane storage because the industrial quality of sugarcane decreases after harvesting. Thus, the sugarcane crop plan can and should be optimized in a way that considers the conditions in which the sugarcane production and the mill are controlled by various agents (Higgins, 2002; Jiao et al., 2005; Le Gal et al., 2009; Piewthongngam et al., 2009) or by a single agent (Grunow et al., 2007; Jena and Poggi, 2013).

The harvesting plan follows the crop plan. The approximate harvest dates have already been considered during the previous planning stage (crop plan). However, for the harvest stage, the plan is refined to reflect the progression of the crop. In general, this planning process, generally conducted at the operational level, is of a rolling-wave nature, and the plots or farms that should be harvested during the following week or month are chosen using the crop plan. The planning process is performed several times

throughout the crop growth cycle, and the characteristics vary depending on the arrangements between producers and mills (Higgins, 2002; Le Gal et al., 2009; Piewthongngam et al., 2009) or on the characteristics of the mills (Grunow et al., 2007; Jena and Poggi, 2013). For the mills, the restrictions are operational, with the goal of maximizing the quality of the raw material. For arrangements between producers and mills, commercial agreements may impose other restrictions.

Although the harvesting plan determines which plots will be harvested at a given time, the sequence of the harvests must still be planned, i.e., the harvests have to be scheduled. For the scheduling, the logistics of moving between various harvesting areas, with varying priorities, are considered with the aim of minimizing the costs associated with harvesting. The harvesting plan can be elaborated with schedule restrictions (Grunow et al., 2007; Jena and Poggi, 2013; Le Gal et al., 2009). There is also the need to revise the plan in the case of critical conditions, such as excessive rains that impede harvesting, or occurrences of traffic, flowering, or frost in a given area, which can result in decreases in the sugarcane industrial quality. In addition to flowering or frost, the occurrence of accidental or criminal fires also requires the area to be harvested as soon as possible. The needs related to harvest prioritization to address extraneous events, while maximizing profit by sugar content, are described by Stray et al. (2012) for the development of a scheduling-based decision support system for sugarcane growers in South Africa.

Yield forecasting is also used while analyzing when to plow and replant (renew) a field. Discounted cash flow models for multi-year periods to account for the successive yield decline in ratoons are used to determine the number of ratoons or minimum yield required to renew a field (Hoekstra, 1976). Tonta and Smith (1996), based on sensitivity analysis, noted the necessity of reviewing the forecasting results for any potential changes in future yield or in economic parameters. In addition to the modeling parameters, the economic criteria exert an influence on this renewal decision. The economic criterion implemented by Hoekstra (1976), the maximization of future profit, may be suboptimal because it is not achieved until the next ratoon has a positive income, leading to harvests with marginally positive results. Salassi and Breaux (2002) recommend the maximization of the mean annual net income as a preferred criterion, and Keerthipala and Dharmawardene (2001) recommended the cumulative return on investment. Based on any of these recommended financial criteria, it is possible to establish the minimum yield required to meet the corresponding economic needs.

Note that forecasting using this approach relies on a chain of information in which the models, the data characterizing production, and the climate forecasts are the basic elements. Yield forecasting can be performed by using yield models in combination with production data and climate forecasts. These yield forecasts can be used in production-system models for decision-making at subsequent levels. Therefore, we start from decisions that are made based on climate forecasts (Everingham et al., 2002), proceed to decisions that are made using climate forecasts and yield models (Meinke and Stone, 2005), and finally consider decisions that require all of this information for planning processes conducted from the operational to the strategic level (Ahumada and Villalobos, 2009).

Of the previously mentioned planning applications, only Piewthongngam et al. (2009) used a yield forecasting model (CANEGRO/DSSAT), whereas the remaining authors used historical averages to develop agricultural plans. Le Gal et al. (2009) highlighted the use of models to improve system representation and suggested that future studies should focus on that use. Two criticisms can be made of the use of historical averages for agricultural planning. First, Ahumada and Villalobos (2009) have noted the need to use stochastic techniques for planning to better reflect the nature of real systems. Higgins et al. (2007) have also referred to the system variability, as previously discussed. In addition to neglecting

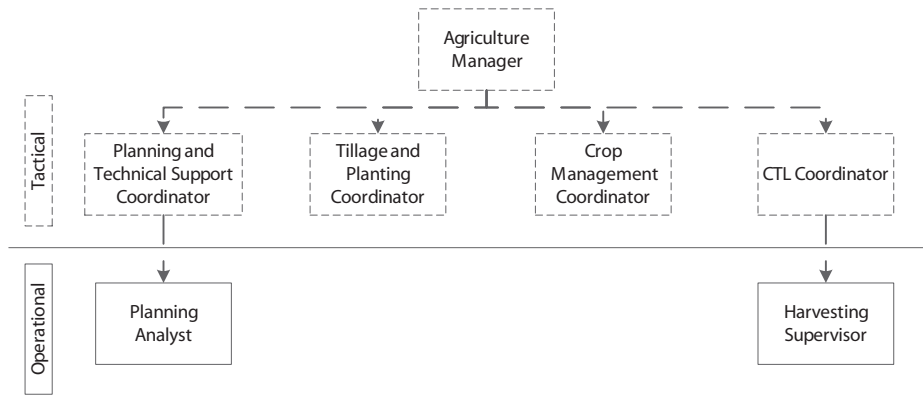


Fig. 2. Partial organizational structure and organizational levels of the interviewed professionals. *Not interviewed.

stochastic characteristics, the use of historical averages assumes a mean historical behavior for the climate and fails to incorporate meteorological information, which has great potential insight for agricultural processes (Hoogenboom, 2000). Notably, the use of models does not guarantee a stochastic response of yield. However, the evaluation of several climate scenarios allows for the estimation of a mean behavior and its variation (Bezuidenhout and Singels, 2007a; Everingham et al., 2002).

Based on the literature review, the main decisions related to producing yield forecasts are the crop plan itself and the influence of the crop plan on the commercial strategy, the harvest plan, and the subsequent sequence of plot harvests. The decision of when to plow and replant a field is based on the field’s harvested yield and is evaluated based on the minimum required economic yield. The crop plan, harvest plan, and harvest schedule present a hierarchical dependence, with a decrease in time horizon (from season to week) and a decrease in spatial scale (from the entire mill to individual fields). The plans also differ in terms of their anticipation of planned activities. The crop plan for the approaching season is elaborated during the season. The harvest plan is first elaborated for the entire season and then re-evaluated monthly or weekly. The harvest schedule is characterized by a weekly rolling-horizon planning scheme.

3. Materials and methods

The present case study is a descriptive, exploratory investigation based on semi-structured interviews requesting information on the planning in the Alcídia mill, operated by Odebrecht Agroindustrial, located in the Teodoro Sampaio municipality, state of São Paulo (SP), Brazil. The unit’s planning practices can be extrapolated to other units of the company (9 in total), corresponding to 24 million tons of sugarcane processed per year across four Brazilian states. The professionals interviewed at the tactical level were the Agricultural Manager, the Planning and Plant Development Coordinator, the Crop Handling Coordinator; and the Cutting, Loading, and Transportation (CLT) Coordinator. At the operational level, a Harvesting Supervisor and a Planning Analyst were interviewed. A partial illustration of the organizational chart that depicts the hierarchical distribution of the interviewed professionals is presented in Fig. 2.

Relevant aspects of the considered agricultural decisions are presented in Table 1. For each decision, the following factors were

recorded: (1) the role of the decision within the organization (Danese and Kalchschmidt, 2011), defined as the aim, a characteristic that is associated with the functional process under consideration (this factor was also surveyed by Ahumada and Villalobos (2009)); (2) the organizational level of the decision; (3) the scale of the forecast/estimate; (4) the relationship between the timing of the forecast and the timing of the final harvest (harvested yield); (5) the relationship between the timing of the forecast and the planning/decision time horizon, as described by Meinke and Stone (2005); (6) the model used in each decision (yield or planning). In their Australian study, Everingham et al. (2002) recorded decisions for multiple links of the sugarcane value chain, which in Brazil correspond to the various functional areas/processes of the sugarcane mill.

The limitations for extrapolating the results of this study to other Brazilian mills or contexts outside Brazil are also noted.

4. Results and discussion

4.1. Forecasting and estimating yield at the sugarcane mill

Multiple professionals interact with the crop at various growth stages. A simplified representation of these interactions is presented in Fig. 3. Planning professionals determine the timing of the establishment of the crop, i.e., planting, and evaluate the crops throughout the entire growth cycle. Following the crop sprouting, the management practices implemented during crop growth vary among crop-handling professionals. During the final crop production stage, CLT professionals are responsible for the harvest and the logistics of the transportation to the industrial unit.

The agricultural planning sector is responsible for producing forecasts at the mill, especially the planning coordinator. The planning coordinator is a specialist in this activity and prepares forecasts according to his tacit knowledge of the sugarcane growth characteristics and the factors affecting yield. In the interview, this specialist was questioned regarding the method by which he performs forecasts, and the structure of the reported method was similar to the hierarchy of yield-limiting factors used in several plant-growth models (e.g., van Ittersum et al., 2003), which consider a sequence of factors that decrease potential yields. According to the specialist, his first forecast for crops at their first ratoon takes into consideration the interactions between Variety × Production Environment × Harvest

Table 1 Table used in the interviews.

| Application | (1) Aim | (2) Organizational level | (3) Scale | (4) When | (5) Time frame | (6) Model |
|-------------|---------|--------------------------|-----------|----------|----------------|-----------|
| What? | Why? | Who? | Where? | When? | When? | How? |

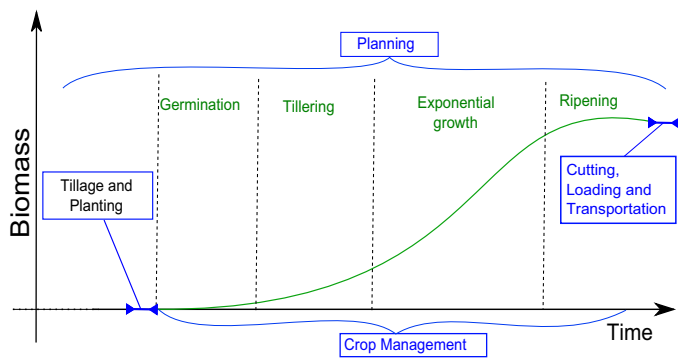


Fig. 3. The first growth cycle of sugarcane and its relationship with the various areas of action within the sugarcane mill. During subsequent cycles, upon sugarcane ratooning, planting professionals are involved in soil preparation.

Time. Naturally, greater yields are expected in the most favorable environments. Regarding harvest time, yields from harvests planted in the beginning of the year are expected to be greater than those planted later in the year. This variation is considered to be the result of the water availability during various sugarcane growth stages, as described by [Inman-Bamber and Smith \(2005\)](#), and the region's rainfall regime. Until the middle of April, there is high water availability during the sugarcane's exponential-growth stage because of the local summer rains, which are critical for determining the final yield. In the areas with late harvests (between August and December), there are higher rainfall volumes at the beginning of sugarcane growth, a stage that does not demand a high water volume because of the low evapotranspiration, while the rapid growth stage occurs during winter of the following year, which is characterized by a lower water availability, which has a negative impact on the yield. The inclusion of the variety in this analysis demonstrates that the implicit knowledge of the specialist is in accord with the strategies applied by plant breeders and research scientists to improve and understand the controlling factors for yield ([Ramburan et al., 2011](#); [Spiertz, 2013](#)). The specialist relates the yield to the characteristics of first cycles, distinguishing sugarcane plants subjected to varying water regimes during different seasons (sugarcane crops with first cycle of either 12 or 18 months or winter sugarcane). This initial forecast includes the first two hierarchical levels of the ordering of yield-affecting factors, which, again, follows the same structure as the growth models ([van Ittersum et al., 2003](#)). Subsequently, the specialist reduces the yield based on his knowledge of the area's history, also considering occurrences of pests and invading plants.

From the second ratoon onwards, yield is estimated based on the previous yield and the occurrences of plant health-related factors and/or problems, such as those from inadequate handling (e.g., treading and uprooting) and farming practices or from occurrences of climate conditions that can affect future yields, such as droughts or dry spells, frosts, or decreases in photoperiod. For each occurrence of an adverse situation or condition, the specialist estimates the potential variation in absolute yield. An evaluation scorecard, on which scores for treading, pests, and flaws are recorded, was developed to assess a sugarcane field with the goal of facilitating the yield forecasting process.

The interviews with the crop handling and CLT coordinators revealed that their interactions with the sugarcane fields at various stages confer tacit knowledge of the sugarcane growth and final yield characteristics and provide them with the ability to perform yield forecasts or estimates, depending on the crop stage at which they act. CLT-associated professionals interact with the crops at the moment of harvesting and, therefore, do not need to forecast the result but are capable of estimating the yield of plots. These

professionals emphasized that their estimates are based mainly on characteristics such as plant diameter, plant height, and number of stalks per meter. While yield is correlated with stem diameter, denser ("closed") sugarcane fields contain a greater number of stalks and consequently produce higher yields. Similarly, the presence of flaws in the planting lines of sugarcane is considered to decrease yield estimates. Notably, these visual inspections are conducted at the borders of plots and thus the heterogeneity within a crop field and border effects may influence the accuracy of these estimates. For CLT-planning purposes, sugarcane fields are evaluated by quality professionals during the week in which a given field will be harvested, under the responsibility of the planning coordinator. This evaluation is therefore a yield estimate.

Because crop-management professionals interact with the crop at the intermediate growth stages, these individuals can consider the crop conditions and extrapolate the results into the future according to an estimated harvesting date. The exchange of information among planning, crop-handling, and CLT professionals allows for differences among previous forecasts to be compared with each other and with other outside information. Because these estimates and forecasts are dependent on professionals' tactical knowledge, the estimates and forecasts cannot be extrapolated to other contexts.

4.2. Decision-making and planning at the mill

4.2.1. Budget, crop plan, and commercial strategy

The widest scope of planning observed from the interviews was the joint-planning of the budget, crop plan, and commercial strategy (storage, spot selling, and/or forward selling) for the following season, which is conducted in August of the current season and based on the specialists' forecasts. This planning process was described as an iterative process of creating compatibility among expenses (budget), production (crop plan), and income (commercial strategy). The planning of the following season before the end of the current season is similar to the planning processes reported for South Africa and Australia ([Bezuidenhout and Singels, 2007b](#); [Everingham et al., 2002](#)). Two commercial planning software applications are used in conjunction as a decision-support tool (iplan and icol from iLab®). The modeling strategy for planning is a combination of constraint programming combined with either linear or integer-based programming, and it is based on the decisions and uses of the mill dataset to forecast the mean yield and the industrial quality from the interactions among the ratoon number, production environment, variety, and harvest time.

The use of a constraint-programming model, which was not considered by [Ahumada and Villalobos \(2009\)](#), is notable. [Lustig and Puget \(2001\)](#) have, however, previously noted a growing use of constraint programming in operational research, especially for sequencing and scheduling problems. The use of means for planning based on a deterministic modeling tool should also be highlighted. A stochastic representation of agro-industrial systems would be more consistent with their behavior ([Ahumada and Villalobos, 2009](#); [Higgins et al., 2007](#)). From a practical point of view, this finding highlights the need to consider constraint programming as a candidate method for planning models used in agriculture, as noted by [Weintraub and Romero \(2006\)](#). A specific application of constraint programming coupled with mixed-integer programming was implemented by [Masoud et al. \(2011\)](#) to optimize sugarcane rail operations and by [Higgins \(2002\)](#) to optimize the harvesting schedule, while a more complex approach was applied by [El Hachemi et al. \(2011\)](#) for the forestry industry, within the context of planning the harvesting sequence and routing of fleets (similar to the planning for a sugarcane harvest).

New crop-plan forecasts are performed in January before the start of the season in March. During each season, two new forecasts are performed throughout the year: one in May and one in

September. As the season progresses and the crops grow, visual field surveys can produce better results, and the data from other areas that have already been harvested, climate data from the area gathered by a specialist, and biomass inventories obtained from remote sensing can also be included in the forecasting. These data help to refine forecasts and identify any necessary changes to plans. To meet the needs of the company, the different mills conduct crop planning simultaneously, relying mainly on the tacit knowledge of the various professionals, each connected to a given unit and area of action. The use of production means incorporates an implicit assumption of the occurrence of a mean climate behavior to overcome the above-mentioned limitations of the lack of data on future climate conditions. The development of subsequent forecasts within this context is similar to the forecasting process realized later in the season by the Mill Group Board in South Africa, as described by [Bezuidenhout and Singels \(2007b\)](#).

4.2.2. Harvest planning and scheduling

The monthly harvest forecasts in a crop plan are refined weekly according to a rolling-wave strategy, providing detailed estimated dates for each harvest during a given month in the harvest plan. The estimated dates have a one-week target horizon, aiming to account for variations between forecasts and the conditions observed in the field and to provide additional time for circumventing adverse conditions. A decision-making process similar to the rolling-wave strategy described for this mill has also previously been described for another Brazilian mill ([Jena and Poggi, 2013](#)), and these strategies are similar to the harvest scheduling process presented for Australian conditions by [Jiao et al. \(2005\)](#) and [Higgins \(2002\)](#). Upon the definition of the weekly harvest plan, daily decisions are required regarding the harvesting schedule for the plots, which should minimize harvesting costs and maintain a flow of raw materials throughout the day. The harvest plan is a tool that is used for crop plan optimization (iCol). Given that the harvest-related planning is based on evaluations conducted one week in advance, methods based on remotely sensed data collected for empirical biomass modeling (e.g., the ones proposed by [Bégué et al., 2010](#) or [Mutanga et al., 2013](#)) could contribute more effectively at this stage than the use of simple yield models (empirical yield or growth models). The adoption of this type of modeling strategy would be limited by the availability of information throughout the crop cycle.

4.2.3. Field renewal and expansion

Yield forecasts were reported to be used for economic evaluations of crop-renewal decisions, though details concerning the economic criteria employed were not disclosed. Interestingly, it was noted that a similar analysis is used to evaluate contracts for rentals in new areas. The previously mentioned commercial software (iplan from iLab®) is also used to optimize crop renewal decisions according to the variety, the production environment, the numbers

of ratoons, and the associated costs of production and CLT, according to the available financial information.

4.2.4. Crop management

Other decisions that were determined to be based on yield forecasts are the management of plant-health, the application of a ripener, and fertilization application. The first two listed decisions are made on demand by the professionals responsible for planning and for plant development and are not connected to crop planning but to the overall agronomic practices at the mill. Fertilization depends on the yield forecast for the first cycle and on the harvested yields for the subsequent cycles. [Everingham et al. \(2002\)](#) consider fertilization to be a decision that should be made during production, whereas [Hoogenboom \(2000\)](#) states that fertilization is one of the main tactical decisions that can benefit from the use of yield-forecasting models in combination with climate forecasts. Nitrogen fertilization planning could benefit from modeling given the plant response to the simultaneous availability of water and nitrogen ([Wiedenfied, 1995](#)) and the dynamics of the nitrogen requirement for the production of sugarcane biomass in the first and subsequent ratoons ([Franco et al., 2011](#)).

None of the questions related to crop handling that were presented by [Everingham et al. \(2002\)](#) was raised in the interviews because of the focus of the study on the influence of climate and rainfall and not necessarily on the optimization of yield. According to [Hoogenboom \(2000\)](#), when discussing the use of growth models for yield forecasting to support planning for rain-fed crops, few of the decisions that are made at the production stage, other than fertilization, can benefit from yield forecasts performed after the conditions of crop establishment have been decided. Handling decisions, such as those related to plant health, depend on the inclusion of appropriate factors in the model.

4.2.5. Overview of decisions and their characteristics

[Table 2](#) summarizes the interview results for the remaining characteristics, as well as the aim/use of the prediction. In addition to the considerations of historical averages and field sampling results, the visual field survey is considered to be a tacit model, dependent on the knowledge and experience of the professionals involved.

The distribution of decisions throughout the organizational levels and along the value chain is presented in [Table 3](#). The concentration of decisions within the cultivation stage, as reflected by the interview responses of agricultural professionals, is notable. The absence of the use of yield forecasts for making decisions that are related to milling and production, which corresponds to the industrial sector, is an important finding. As a result of the industry's characteristics, these decisions are more connected to the planning of milling operations at various time scales (daily, weekly, monthly, and entire crop cycle). Obviously, the quantity of material that is supplied to a mill depends on the yield and the area of

Table 2
Decision-making characterization.

| Application | Level | Scale | When | Time frame | Model |
|--|-------------|-----------|--------------------------------|----------------------|--|
| Budget Commercial strategy Crop plan Renovation and expansion contracts | Tactical | Mill area | Aug–Jan of the previous season | Seasonal (~9 months) | Specialist, tacit modeling and historical averages |
| Harvesting plan Harvest schedule Application of ripener Application of pesticides Fertilization at the first cycle | Tactical | Farms | Continuous | 5 years ^a | Historical averages and Specialist, tacit model |
| | Operational | Mill Area | Weekly | Weekly | Specialist, tacit model |
| | Operational | Farms | Daily | Daily | Field sampling |
| | Operational | Plot | Seasonal beginning | 20 to 40 days | Specialist, tacit model |
| | Operational | Plot | Variable | Intra-crop | Specialist, tacit model |
| | Operational | Plot | Continuous | Plot planting | Specialist, tacit model |

^a In the case of expansion, the strategic decision is made considering a longer interval. However, the evaluation of areas generally considers a typical 5-year cycle, with areas incorporated throughout the growing season.

Table 3
Distribution of decisions made at various organizational levels (separated by dashed lines) along the value chain (horizontal). Decisions with longer time frames are listed at the top of the table, and the remaining decisions are presented in a vertically decreasing order. This table summarizes the relationships among the decisions in Table 3 and the organizational structure depicted in Figs 1 and 2.

| | Input | Cultivation | Harvesting and transportation | Milling and production | Sales |
|-------------|--|---|-------------------------------|------------------------|---------------------|
| Tactical | | Contracts for expansion Renovation Crop plan | | | |
| | Budget | | | | Commercial strategy |
| | Harvesting plan Harvesting schedule | | | | |
| Operational | | Chemical control Application of ripener Fertilization | | | |

the harvested plots. However, it is the responsibility of the CLT professionals to manage this relationship between plot yield and the flow of raw material to milling operations. A similar reasoning applies to sales strategies, for which the yield of each plot contributes to the forecast of the total quantity of raw material available for sugar and ethanol production.

4.3. Perspectives for yield and planning models used in decision-making

Based on the literature review and on the case study, it is evident that the hierarchical relationships among the agricultural decisions and the decisions themselves are based on the forecasted or estimated yield. The use of mathematical/computational techniques for enhanced or optimized decisions or planning has also been observed. The concept of integrated planning in a hierarchical form, i.e., hierarchical planning and the use of mathematical/computational models to enhance planning, are ingrained in APS for Supply Chain Management (SCM). These systems are considered to represent a significant progression in relation to an Enterprise Resource Planning Systems (ERP) capabilities. The use of an APS with an ERP database and the integration of various planning processes can support the realization of an optimal result for the entire chain, avoiding situations of local optima for each plan (Fleischmann and Meyr, 2003). Although the concept of APS is not new (Stadtler, 2005) and it is considered a state-of-the-art technology (Stadler and Haub, 2012), neither the literature reviewed nor this case study have considered planning from this point-of-view.

According to Kreipl and Pinedo (2004), integrated-systems approaches must include a feedback mechanism within the tool for integrated planning because it is necessary to ensure the alignment between the plans at the multiple hierarchical levels. In addition, given the characteristics of sugarcane production, a feedback mechanism is also necessary to evaluate the evolution of plans and to eventually revise a plan because of the availability of new information. This new information can be supplied in the form of new yield forecasts or harvested yields, or it can describe a stochastic event, such as machine failures (e.g., harvester or in the mill) or traffic restrictions at the time of harvest or route restrictions caused by rain events.

In the APS literature, there is a concern related to the production of demand forecasts for multiple levels of planning, namely, that this approach could result in inconsistency among plans (Fleischmann and Meyr, 2003), a phenomenon that can hinder organizational performance (Danese and Kalchschmidt, 2011). The same consideration applies to production forecasts (in this case, sugarcane yield forecasts). From this perspective, it is necessary to address the consistency among approaches (e.g., bottom-up aggregation) to maintain consistency among multiple plans, and also to address the uncertainty related to these predictions.

There is significant emphasis placed on the demand uncertainty in Supply Chain Management (SCM). Hence, the usual deterministic approach for process in SCM is not suitable for the sugarcane complex because the high level of process uncertainty is undeniable and must be addressed (Ahumada and Villalobos, 2009; Higgins et al., 2007). In a review of supply-chain planning uncertainty, Peidro et al. (2009) noted that among the 103 references reviewed, 59.22% of the models only considered one source of uncertainty, while 29.13% considered two sources and only 9.71% considered all three sources (supply, process, and demand uncertainties). In their results, notably, only 15 of the models addressed process uncertainty.

A more intensive use of data for production planning has also been advocated by Lawes and Lawn (2005), who reported on the application of such data to decision-making, complementing other types of more conventional approaches. This integrated use of forecasts for decision-making and planning is in accordance with the requirement for better integration among various functional chains (Bezuidenhout and Baier, 2011). In this case, a better level of integration between the information chain and the value chain, with gains in the transportation and material handling chain, should be considered and developed.

While the optimization of the entire value chain to avoid local optima is a reasonable goal for a value chain managed by a single agent, this outcome is not simple within a multi-agent context. Several aspects for collaborative planning have been discussed by Stadtler (2009), who also noted the need to address fairness in the distribution of the supply chain gains among the various members and the need for collaborative schemes that allow for the renegotiation of accepted plans and for rolling schedules. Given the uncertainty concerning agricultural production, the second suggestion could be critical for the adoption of such schemes. The use of a common database for forecasting was reported by Danese and Kalchschmidt (2011) to be one of the variables of the forecasting process that has a positive effect for manufacturing companies, and there is no reason to presume that the relationship would be different for the sugarcane complex. These authors also proposed that information should be collected from multiple sources, such as consumers, economic stakeholders, and suppliers.

The use of APS for agricultural planning can address the integration of plans that can be optimized and enhanced through mathematical/computational models. This level of integration can ensure the alignment of plans and the common use of data. In addition to the considerations regarding the actual parameterization of an APS, the APS developed for agricultural planning must consider production forecasts for yield and their stochastic characteristics to effectively represent the characteristics of the production system.

5. Conclusions

The various contexts of decision-making impart variations in the timing of decisions, with variations in the availability of

information. The development of yield models or decision-support tools based on modeling must account for this variation, in particular, when model/tool development has the unique purpose of evaluating a practical planning issue.

An incremental increase in the amount of available information is expected as the growing season progresses, allowing for better forecasting and planning. This incorporation and use of new information also has consequences, given that the fields are managed in various stages of development, allowing for better forecasting in some fields than others. A more comprehensive study of this topic should be considered in future studies. Furthermore, as indicated by the results of Danese and Kalchschmidt (2011), there are other factors that should be considered for forecasting in addition to the forecasting error, which was the least influential variable in terms of operational performance.

Several modeling strategies are available for sugarcane yield forecasting, ranging from growth models to empirical models based on remotely sensed information. Yet the majority of the decisions observed in the case study and in the reviewed planning models are based on the mean yield. In addition, the decision-making and planning processes, as well as the reviewed planning models, are based on deterministic approaches. The use of mean yields in a deterministic approach suggests a gap between the understanding of the system and the information used in decision-making.

Although APS are usually proposed for SCM, within the context of this application, APS should also evolve to include yield forecasts to quantify production and should address the uncertainty in yield forecasts. The capacity of APS for integrated planning and the use of mathematical/computational methods to enhance planning are viewed as advances in the planning context.

From a general perspective, yield forecasts and crop evaluations are based on a specific plan or decision for which the forecast/evaluation has been developed. A supply-chain view should be adopted when evaluating the forecasting error and its consequences. Supply chain simulations can simulate the impacts of uncertainty and error in forecasting and in the subsequent elements of the supply chain. Future research should also evaluate the degree of accuracy that is required for various planning contexts and evaluate the approaches by which available modeling strategies can provide useful insights for planning.

Based on the decisions reported in the literature and observed in the case study, the budget, crop plan, and commercial strategy are considered critical because of their effects on the entire value chain and because of the high uncertainty associated with the timing of decision-making.

The list of decisions presented in this work can be used in future studies conducted in this sector in the form of a questionnaire. In addition to measuring the adherence to the identified planning and decision-making structure in other sugarcane-production units, variations in this process could be measured and related to the operational performances of sugarcane mills, similar to the approach employed by Danese and Kalchschmidt (2011). The use of remote-sensing technology, modeling methods, planning models and tools, and climate forecasts also require further investigation.

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