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Production planning in sugarcane mills: new biogas technologies and optimal decisions

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To my future self*, so I can look back and remember that the combination of hardwork, resilience and a little bit of cleverness leads to great achievements.*

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With all my gratitude,

Victoria Morgado Mutran

"A diamond is a chunk of coal that did well under pressure."

(Henry Kissinger)

Abstract

MUTRAN, Victoria Morgado. **Production planning in sugarcane mills:**: new biogas technologies and optimal decisions. 2021. 94 p. Thesis (PhD) – Polytechnic School, University of São Paulo, São Paulo, 2020.

The sugarcane industry in Brazil is one of the most relevant agricultural activities, greatly contributing to the domestic economy since the colonial times. Over the past 70 years, many public policies have affected the sugarcane business, placing sugarcane mills as important players in the national energy matrix as liquid fuel producers and electricity suppliers. Recently, studies have examined the potential use of biomass residues (bagasse and vinasse) for energy purposes. However, market conditions in recent years have not been sufficiently attractive for producers to invest on new bioenergy generation, which calls for governmental interference. This project aims to support bioenergy in the Brazilian sugarcane industry by addressing the question of how to effectively incentivize bioenergy generation. Given the complexity of producers' production and investment decisions, the methodological approach is computational by nature, and entails the application of portfolio theory in combination with surrogate modelling and superstructure optimization. The proposed optimization frameworks are illustrated in representative case studies, allowing key insights to be drawn. Results obtained based on historical prices showed a clear tendency for a sugar-oriented business, contradicting the expectation of interviewed experts for a future based on energy products. Prices in the regulated market of electricity were shown to play a relevant role in attracting an increase in generation efficiency, while the investors production and investment decisions show a high sensitivity to price risks. In addition, a detailed process modelling allowed for more reliable decision-making, and showed that simplified models may lead to risky investment decisions and shortfalls. Finally, as for technological routes, ethanol 2G is still not advisable at current investment costs, but biogas generation shows great potential for all three economic applications: diesel displacement, power generation and commercialization as piped gas.

Keywords: Bioenergy, Risk, CVaR, Sugarcane.

Resumo

MUTRAN, Victoria Morgado. **Planejamento de Produção em Usinas de Cana de Açúcar: novas tecnologias de biogás e decisões ótimas.** 2021. 94 p. Thesis (PhD) – Escola Politécnica, Universidade de São Paulo, São Paulo, 2020.

A indústria da cana-de-açúcar no Brasil é uma das atividades agrícolas mais relevantes, tendo contribuído fortemente para a economia nacional desde a época colonial. Nos últimos 70 anos, diversas políticas públicas afetaram o negócio da cana-de-açúcar , colocando as usinas como importantes atores da matriz energética nacional, tanto como produtoras de combustíveis líquidos quanto como fornecedoras de energia elétrica. Recentemente, estudos têm examinado o potencial uso de resíduos de biomassa (bagaço e vinhaça) para fins energéticos. No entanto, as condições de mercado nos últimos anos não têm sido suficientemente atrativas para os produtores investirem na nova geração de bioenergia, o que exige interferência governamental. Este projeto visa dar suporte à bioenergia na indústria canavieira brasileira, abordando a questão de como efetivamente incentivar a geração de bioenergia. Dada a complexidade das decisões de produção e investimento dos produtores, a abordagem metodológica é computacional por natureza e envolve a aplicação da teoria do portfólios em combinação com otimização de superestruturas por aproximações. As estruturas de otimização propostas são ilustradas em estudos de caso representativos, permitindo que as principais persepções sejam extraídas. Os resultados obtidos com base em preços históricos mostraram uma tendência clara para um negócio orientado para o açúcar, contrariando a expectativa dos especialistas entrevistados, que acreditam num futuro para o setor baseado em produtos energéticos. Os preços no mercado regulado de energia elétrica mostraram ter um papel relevante na atração de investimentos em aumento na eficiência da geração, enquanto as decisões de produção e investimento apresentam elevada sensibilidade aos riscos de preço. Além disso, a modelagem mais detalhada do processo permitiu uma tomada de decisão mais confiável e mostrou que modelos simplificados podem levar a decisões de investimento com alto risco. Por fim, quanto às rotas tecnológicas, o etanol 2G ainda não é aconselhável nos atuais custos de investimento, mas a geração de biogás apresenta grande potencial para as três aplicações econômicas: substituição de diesel, geração de energia e comercialização como gás canalizado.

Palavras-chaves: Bioenergia. Risco. CVaR. Cana de Açúcar.

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1 Introduction

1.1 Background and Motivation

Environmental concerns have become a widely discussed topic. Arguments on global warming due to greenhouse gas (GHG) emissions have led governments worldwide to implement environmental regulations, in addition to incentives for renewable energy sources (Pereira et al, 2012). In Brazil, some important public policies have greatly affected one of its most traditional agricultural sectors, the sugarcane industry, introducing it firstly to the liquid fuel business, by the production in large-scale of ethanol, and later on into the electricity matrix, with power generation from the combustion of sugarcane bagasse, a now valued by-product due to its several potential uses (Hofsetz and Silva, 2012).

While the ethanol production has placed the country as one of the largest biofuel producers in the world (FAO, 2019), the generation of problematic residues from the process, bagasse and vinasse, poses even greater challenges. Nearly 30% of all sugarcane processed is turned into bagasse, whilst for every liter of ethanol produced, an average of 10 to 12 liters of vinasse is generated (Leme and Seabra, 2017).

Alternative uses for bagasse have been developed over the past 30 years, as an effort to find environmentally friendly destinations for it, even though there is still room for improvement in energetic efficiency in its applications — being the two most relevant potential uses the ethanol 2G and power generation. Vinasse, on the other hand, is still an important issue for producers, as the residue may present adverse environmental effects, such as water contamination and soil deterioration (Christofoletti et al, 2013). Therefore, an increasing body of research has recently focused on the technical and economic feasibility of biogas generation from such vinasse residues (Moraes et al, 2014; Bernal et al, 2017; Pazuch et al, 2017; Leme and Seabra, 2017).

Despite the existing opportunity to increase renewable energy participation in the Brazilian energy matrix with biomass residues from the sugarcane industry, and to the number of technological routes that are now available to do so, recent market conditions have not been sufficiently attractive for producers to invest in new bioenergy projects. From the producers' perspectives, bioenergy is generally seen as a secondary economic activity which poses several uncertainties regarding investment returns and process feasibility. Particularly because there's been a historical price volatility for sugar and ethanol, while there's also a lack of a clear and long-term governmental policy towards bioenergy (Hughes et al, 2020).

On the other, from the policymakers' point of view, it is a challenge to create efficient price policies to attract new bioenergy generation, especially since Brazil is a country with abundant sources of renewables. In fact, Brazil has been for many years a leading country in terms of renewable energy, with sugarcane figuring as the main renewable source (see Fig 1). And even so, Brazil has recently signed the Paris Agreement (UNFCCC, 2018) committing to so-called nationally determined contributions (NDCs), which aim to achieve 45% of renewables in the energy mix by 2030 and to reduce the country's GHG emissions by 43% below 2005 levels.

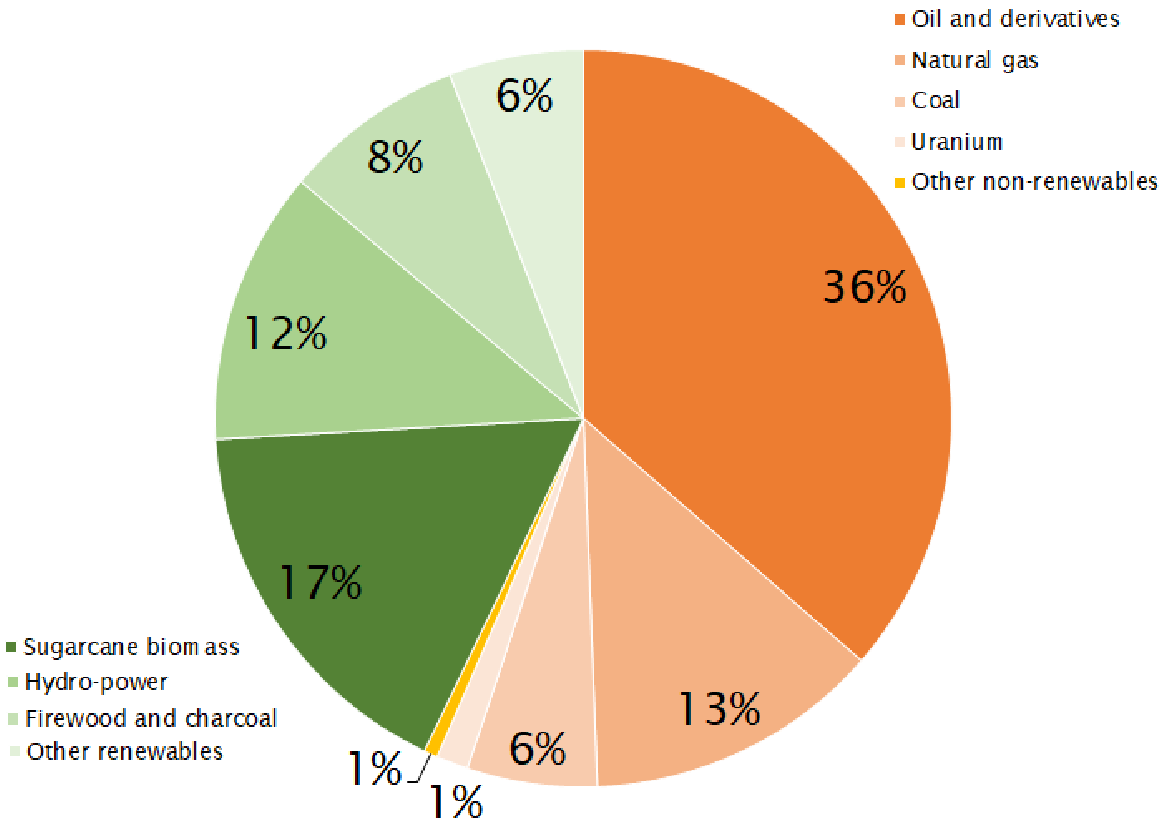

Figure 1 – Brazilian energy mix in 2017 (Source: EPE, 2018)

In this context, the Brazilian government has introduced RenovaBio, a national policy aiming to increase the use of all biofuels — including ethanol — in order to improve energy security and achieve the aimed reduction in GHG emissions. Under RenovaBio, the demand in hydrous ethanol is expected to rise from 15.2MM m^3 in 2018 to 36MM m^3 by

2028, with projected investments of about US$15Bn in ethanol supply, including expansion of existing biorefineries, installation of new sugarcane and corn facilities, and investment in 2G ethanol production (ANP, 2019).

RenovaBio has brought a common sense of optimism into the sugarcane sector (Hughes et al, 2020), but there's still a lot of uncertainty on future market conditions, on what policies should be put in place to attract these investments, and on what decisions the producers should make in response to them. Thus, there's a clear need for a reliable decision-making system to assist producers and policymakers under these uncertain market scenarios.

Recent studies have tried to address some of these decision-making challenges in the assessment of new technologies for bioenergy generation (Grisi et al, 2012; Furlan et al, 2012; Carpio and Souza, 2017; Dutenkefer et al, 2018). But there's still a relevant theoretical gap, as the proposed models so far haven't captured the interdependencies between price risks and process feasibility in the context of new investments on bioenergy projects. In the following section, this identified opportunity for theoretical contribution will be further detailed.

1.2 Relevance to the literature

Introduced by Henry Markowitz (1952), Modern Portfolio Theory empowers a formal description of the effects of diversification in investments. Markowitz's theory provides a method - via an optimization model - to identify how good a given portfolio is, based on the risk and the expected return of the assets in the portfolio. Over the past few years, this approach has transcended its traditional application within the financial markets into various sectors, including engineering (Paydar and Qureshi; 2012; Francés et al, 2013; Costa et al, 2017). A recent and popular application of Modern Portfolio Theory is concerned with product mix decisions, as a means to deal with uncertainty in production planning (Carpio and Souza, 2017; Dutenkefer et al, 2018). This is the case for the sugarcane market in Brazil in particular.

Carpio and Souza (2017) proposed an optimization model based on the Modern Portfolio Theory (Markowitz, 1952) to find the optimal distribution for the use of surplus bagasse in sugarcane mills: selling power in the free market, in the regulated market or its use for the production of second generation ethanol. The study showed that most of the surplus bagasse should be distributed between ethanol 2G and bioelectricity sales to the regulated market, with distribution being proportional to the level of aversion to risk. A few limitations of this study are that it did not take into account other products in the mill, it considered a fixed availability of bagasse (which in reality is variable), and it did not consider investment costs (which in the case of ethanol 2G are very high) — three very important factors when assessing the potential uses of bagasse.

Another drawback from the model developed by Carpio and Souza (2017) is that it used variance as a risk-measure. Even though this is as originally proposed by Markowitz, the variance is not always appropriate, since it penalizes identically negative and positive deviations from the expected return. The development of risk management theory has led to significant advances in the understanding of risk measures. Downside risk measures, such as Semivariance, Value at risk, Conditional value at risk, and Conditional Drawdown at risk, have been considered as alternatives to variance in portfolio theory as they only penalize the chance of getting below a given expected return. From these measures, the Conditional Value at Risk (CVaR), proposed by Rockafellar and Uryasev (2000) has been successfully applied in portfolio management due to the possibility of solving the resulting optimization problems using linear programming.

Dutenkefer et al. (2018) proposed an optimization model using CVaR as the risk measure, and considered fixed parameters from literature for process conversion rates and efficiencies, which were determinant for the portfolio decisions found.

Nevertheless, the changes in the shares of products in sugarcane mills may affect the optimal process conditions, such as demand for steam and electricity (Furlan et al, 2012; Castro et al, 2018). That is, these operational parameters are themselves functions of the production mix decision variables. Thus, in order to take those process changes into account, it would be necessary to include mathematical models describing the process units in the formulation of the operational constraints for the risk-return optimization.

Surrogate-based superstructure optimization has been vastly used to reduce the complexity of the problem, because "when realistic unit operation models are used, then the resulting models cannot be solved" (Henao and Maravelias, 2011). Thus, surrogate models, also known as reduced-order models, have been used to simplify complex models by speeding up the exploration of solution spaces through "surrogates", which are often statistical regression functions (Wang et al, 2014). Henao and Maravelias (2011) presented a comprehensive methodology for this framework to be used in chemical engineering applications. The surrogate-based superstructure approach was also used to assess technological routes for biogas production in wastewater recovery plants (Puchongkawarin et al, 2014).

Hence, this may be a relevant method to address the decision problems in the sugarcane industry. In fact, a similar approach was developed by Furlan et al (2012), in which the study assessed the use of bagasse in a sugarcane mill, considering its possible destination for second-generation ethanol, steam production, electricity generation, and commercialization of the surplus. In the referred framework, a tool that jointed global optimization with the detailed modeling and simulation of the whole integrated bio-refinery was proposed. A few limitations of the study are that it didn't take into account the price risks, and it analysed the implications of production decisions solely for bagasse destinations.

Therefore, this thesis is justified as a proposal to address limitations of similar studies in literature. Even though Furlan et al (2012) considered the non-linearities in process conditions, they assumed fixed prices for the assets. In addition, their study could only assess the possible destinations of bagasse from a single bio-refinery. Dutenkefer et al (2018), on the other hand, considered the variation in prices (which implies financial risks), but under fixed process conditions and also for a single mill.

Furthermore, evidences show that large-scale production and the shares of ethanol and sugar may have great impacts on the economic returns of biogas projects (Bernal et al, 2017), which advocates the need for modeling the interaction of a group of sugarcane mills for assets exchange (in this case, bagasse). Nowadays, it is a common practice in the sugarcane industry to exchange biomass, especially due to the fact that many mills belong to the same economic cluster. Thus, including logistic decisions can be relevant while assessing investment decisions (especially for biogas generation) and product portfolios of mills, which were also not considered by Furlan et al (2012), Carpio and Souza (2017) and Dutenkefer et al (2018).

The present work aims to combine portfolio optimization methods with advanced techniques based on process superstructure optimization in order to enable risk-conscious, optimal decisions for product portfolios and new bioenergy investments in the sugarcane industry. The specific objectives designed to reach this goal will be discussed in the following section.

1.3 Objectives and research question

The main objective of this research is the development of a more reliable decision-making system to support new bioenergy generation in the sugarcane industry. Given the complexity of producers' production and investment decisions, the methodological approach is computational by nature, and entails the application of portfolio theory in combination with surrogate modeling and superstructure optimization.

The proposed decision-making system addresses several key questions related to the use of biogas in the bio-ethanol industry as part of the project **Sustainable Gas Pathways for Brazil: from microcosm to macrocosm**, and aims to answer the following research question: *how to improve decision-making to efficiently incentivize bioenergy generation in the Brazilian sugarcane industry?*

For the development of this decision-making approach, this research was designed to meet the specific objectives enumerated below.

- **OBJ1:** to collect historical data from the Brazilian sugarcane sector in order to understand past dynamics and main factors affecting production of its main products;
- **OBJ2:** to identify future perspectives for bioenergy generation in Brazil;
- **OBJ3:** to understand what role governmental policies may play to incentivize bioenergy sources;
- **OBJ4:** to assess the role of prices practiced in the power sector on investment decisions to increase bioenergy generation in sugarcane mills;
- **OBJ5:** to assess how price risks affect production mix and investment decisions;
- **OBJ6:** to analyse the use of surrogates to solve the portfolio optimization model;
- **OBJ7:** to evaluate technological routes for the use of the main biomass residues in the industry: bagassse and vinasse;
- **OBJ8:** to address economic, infrastructural and logistical challenges in implementing biogas generation in sugarcane mills;
- **OBJ9:** to take into account key process aspects in order to make reliable investment decisions, by incorporating process models, through the use of surrogates, in the economic assessment of new bioenergy processes.

1.4 Structure of this thesis

This Thesis was developed as a collection of five research articles, which individually address the main goals described in Section 1.3.

The Thesis is structured as follows. This first introductory part presents the main research goals, methods and findings. Each paper is presented as a step in the research process, contributing to the achievement of the main research objective. The results drawn from each study in the collection are analysed and discussed in light of their contribution to responding the overall research question of the Thesis. Finally, a conclusion of the overall work and practical implications of the collection of papers are detailed. The 5 Research Articles are then presented in the original form they were published (or submitted) as Appendices. Table 1 summarizes the papers that compose this collection.

Table 1 – Collection of publications that compose the Thesis

Research Article	**Journal / Conference**	**Title**	**Objectives**	**Authors**	**Appendix**
#1	Biomass & Bioenergy	Strength in diversity? Past dynamics and future drivers affecting demand for sugar, ethanol, biogas and bioelectricity from Brazil's sugarcane sector	1-3	Hughes[a], Mutran[b], Tomei[a], Ribeiro[b], Nascimento[c]	A
#2	Computer Aided Chemical Engineering	Risk-conscious approach to optimizing bioenergy investments in the Brazilian sugarcane industry	3-5	Mutran[b,d], Ribeiro[b], Nascimento[c], Chachuat[d]	B
#3	Computer Aided Chemical Engineering	Bioenergy investments in sugarcane mills: an approach combining portfolio theory with neural networks	6-7, 9	Mutran[b], Ribeiro[b], Nascimento[c], Rego[b]	C
#4	2nd LA SDEWES Conference	Biogas in the Brazilian sugarcane industry: addressing logistic and economic challenges	4,5, 7,8	Mutran[b], Ribeiro[b], Rego[b], Chachuat[d], Nascimento[c]	D
#5	Applied Energy	Risk-conscious optimization model to support bioenergy investments in the Brazilian sugarcane industry	3-5, 7,9	Mutran[b,d], Ribeiro[b], Nascimento[c], Chachuat[d]	E

a: UCL Institute for Sustainable Resources, University College London; *b*: Production Engineering Department, Polytechnic School, Univeristy of São Paulo; *c*: Chemical Engineering Department, Polytechnic School, Univeristy of São Paulo; *d*: Centre for Process Systems Engineering, Imperial College London.

2 Literature Review

2.1 The Brazilian sugarcane industry

2.1.1 The sugarcane process

The sugarcane industrial process starts as sugarcane, the main resource in this industry, arrives in the processing plants from cultivation areas. The first stage is the sugarcane milling. The stalks of cane are received and washed to remove excessive trash before entering the extraction system. Subsequently, they are reduced into small pieces by rotating knives and shredders to be then fed to a series of three to five mills, in which raw sugarcane juice is extracted by compression. Electric drives have been lately preferred over steam turbines for the extraction process, as the latter is less efficient in regards of steam consumption (Dias et al, 2015).

The milling process produces two outputs: sugarcane bagasse and juice. Bagasse, the fibrous residue from the extraction process, is broadly used in cogeneration systems to supply the process's demands for steam and electricity. Today, all sugarcane plants in Brazil are self-sufficient in regards of thermal, mechanical and electrical energy. However, the majority of them still operates with low efficiency systems based on traditional Rankine cycles, which result in limited surplus power generation (Ensimas et al, 2007; Hofsetz and Silva, 2012). Thus, given this opportunity for improvement, a number of recent studies has examined potential technological routes to increase efficiency in bioenergy generation with surplus bagasse, which will be discussed in the following section.

The extracted sugarcane juice is directed to the treatment system, since it contains impurities that need removing prior to downstream processing. In this treatment stage, there are a set of unit operations that mainly consist of juice heating, precipitation and filtration. The resultant clear juice is then sent to either ethanol distillery or sugar factory.

Most Brazilian sugarcane mills operate in an integrated plant, in which sugar and ethanol are produced simultaneously. Product mix decisions regarding the shares of juice used either for sugar or ethanol production are limited by the process installed capacities and are usually based on market conditions at the beginning of the season, especially as both of these commodities have historically faced extremely volatile prices. As a strategy for risk-mitigation, sugarcane processing plants have certain flexibility in their process capacities, giving them the possibility to move their production towards sugar or ethanol motivated by the prices in each season.

Heretofore, most operations are common for both sugar and ethanol production. Now, the sugar and ethanol processes will be further detailed to give a comprehensive understanding of the unit operations involved, as well as the different process demands for steam and electricity, which directly impact the availability of surplus biomass resources for energy generation purposes.

Sugar factory: Dias et al. (2015) describe the sugar production processes. The clarified sugarcane juice directed to sugar production has to be concentrated in order to reach an adequate content of soluble solids for sugar, namely the Brix, which goes from around 15° Brix to 65° Brix in the concentration process. This is done in a multiple-effect evaporator, in which exhausted steam from the cogeneration system is used in the first evaporation effect, separating part of the water from the juice, which is subsequently used as source of heating for the next evaporation effect. Vapour bleed from the first and second effects may be used as thermal energy source in other processes, such as treatment heaters, sugar boiling systems and ethanol distillation columns.

The concentrated juice resultant from the evaporation process is called syrup. Prior to crystallization of sugars, it is boiled in vacuum pans forming a mixture of syrup and sugar crystals. Then, the mixture is directed to crystallizers (mixing tanks with cooling systems) to complete crystal enlargement. The sugar crystals are then centrifugated to be separated from molasses. In the centrifugal, hot water and steam are used to wash crystals.

Maximum crystallization cannot be achieved in one-step (Castro et al, 2018). Since molasses are used as a feedstock for ethanol production in most Brazilian sugarcane mills, it is not necessary to completely exhaust them. Thus, in Brazil two-boiling scheme is the most common. Finally, after centrifugation, sugar crystals are dried with exhaust steam to reduce the moisture content of sugar, then cooled and stored.

Ethanol distillery: The first step of ethanol production is fermentation, a biological process that converts sugars into cellular energy, producing ethanol and carbon dioxide (Castro et al, 2018). There is also an adequate sugar concentration for the input mixture that must be achieved in order to have a successful fermentation process. In integrated sugar and ethanol plants, in which molasses resultant from the sugar process are also used as a feedstock for fermentation, it is necessary to concentrate part of the clarified juice destined to ethanol production in order to reach the overall required solid content in the mixture (of clear juice and molasses). Generally, standard evaporators are applied for this concentration process, and the resultant vapour bleed may also be used as utility in other processes.

As described by Dias et al. (2015), conversion of sugars into ethanol usually takes place in a fed-batch fermentation process with the use of recycled yeast (Saccharomyces cerevisiae) recovered from previous batches, which react with the mixture of molasses and clarified juice producing a fermented liquid (wine) with relatively low ethanol content, less than 10% in mass basis. The wine is centrifuged to remove yeast cells and then sent to the next process, distillation.

Ethanol content produced in fermentation is recovered from wine in distillation and rectification columns. Prior to the first distillation, fermented liquor must be heated to achieve temperature requirements. Fuel or hydrous ethanol (around 93wt%) is produced in a relatively simple distillation process, by stripping and rectification stages. In order to remove the remaining moisture content from ethanol, and produce the so-called anhydrous ethanol (around 99.3 wt%), a dehydration process is required (Dias et al, 2015).

The bottom-product of the ethanol distillation process is the vinasse, or stillage, a suspension of organic and mineral solids containing wine components, which include residual amounts of sugar, alcohol and heavier volatile compounds. It is rich in nutrients and its current main use is for fertirrigation of sugarcane cultivation areas, although its direct application as a fertilizer has several downsides, such as potential damages to soil, underground water contamination and unpleasant odour (Christofoletti et al, 2013). Thus, recent studies assess the technical and economic feasibility of producing biogas from vinasse (Salomon et al, 2011; Moraes et al, 2014; Pazuch et al, 2017).

2.1.2 The role in the Brazilian energy sector

The sugarcane sector was firstly introduced to the energy market in the 1970s, as a liquid fuel supplier. In 1975, one of the most relevant public policies in Brazil was launched, the Brazilian Alcohol Program (PROALCOOL), aiming to reduce the country's dependency on oil imports (Franco et al, 2015). PROALCOOL marks the first step towards

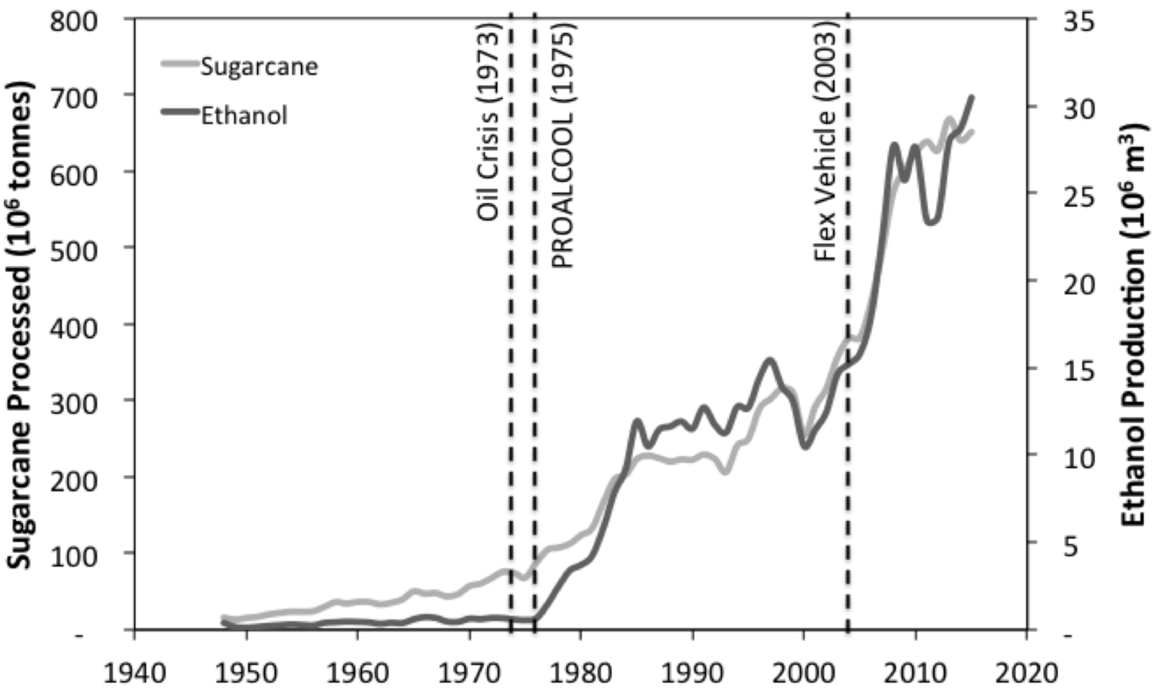

Figure 2 – Evolution of Sugarcane and Ethanol Production in Brazil (based on CONAB, 2012)

the current position of this industry as the main source of renewable energy in Brazil (Lin et al., 2017).

The successful implementation of ethanol production in large-scale has changed the sugarcane business and put the sector in a continuous trend of growth (See Fig. 2). Today, Brazil is consolidated as the largest sugarcane producer in the world, with volume greater than the sum of the six remaining nations (FAO, 2019). In the crop of 2017-2018, Brazilian mills processed approximately 641 million tons of cane (out of which 357 million tons were produced in the state of São Paulo), while the ethanol production in Brazil reached about 28 million cubic-meters.

As the industry followed an expressive increase in production over the past decades, the generation of industrial waste also gained greater proportions. In the 1980s, new regulations have forced sugarcane producers to find environmentally friendly alternatives for biomass residues generated in the agricultural and industrial processes, leading to their entrance to the Brazilian Electricity Supply Industry (BESI). In the beginning of the following decade, almost all Brazilian mills were power-sufficient, but the efficiency of generation was very low due to the inexistence of a market for the surplus electricity (Hofsetz and Silva, 2012).

This scenario started to change in the 1990s, as the need for matrix diversification was prioritized in the agenda of energy policymakers, in the occasion of the BESI reforms (see Araújo et al., 2008). The national electricity matrix has been historically based on hydropower due to earlier governmental policies, which places Brazil among the countries with the largest shares of renewable energy in the world. On the downside, however, the BESI is highly dependent on natural conditions, such as rainfalls, which raises the risks for instability in supply. These risks may be evidenced by cyclical crises (years 1924, 1944, 1955, 1964, 1986, 2001 and 2015) suffered in the power sector, which have shortages in water among their main causes (Hunt et al., 2018).

In this context, the sugarcane industry is called upon to play an important role as a reliable power supplier. Sugarcane mills have a relevant advantage as the peak of the surplus energy generation coincides with the periods of low productivity for hydropower plants, due to lower water availability (Hofsetz and Silva, 2012). Additionally, it is a seasonal activity, not intermittent, which brings more stability to the system. It also presents location advantages as the majority of sugarcane-processing plants are in the Southeast region, the load centre in the country. Further, it is an environmentally friendly activity, complementing the production of ethanol, which also reduces the total national consumption of fossil fuels, such as gasoline.

Those advantages as a power supplier, however, are not currently remunerated. In general, the BESI does not price neither the positive externalities nor the attributes of sources for electricity generation. This means that clean sources located close to the centre of load for electricity demand, which is the case of the sugarcane industry, are paid the same price per MWh that is practiced for fossil fuel plants located anywhere in Brazil. In such a way, under regular market conditions, the associated investment costs are still not competitive in relation to many other sources in the matrix, especially hydropower plants and wind farms. Nalan et al. (2009) points these cost-benefit disadvantages as one of the main barriers to Renewable Energy Sources (RES). Thus, government interference was still in need to ensure the growth in installed capacity of the sugarcane sector.

The Brazilian government has made some efforts in this sense. The first big step was the Alternative Energy Sources Incentive Program (PROINFA), which was established in 2002 with aims to subside new power generation projects for three sources: wind, biomass

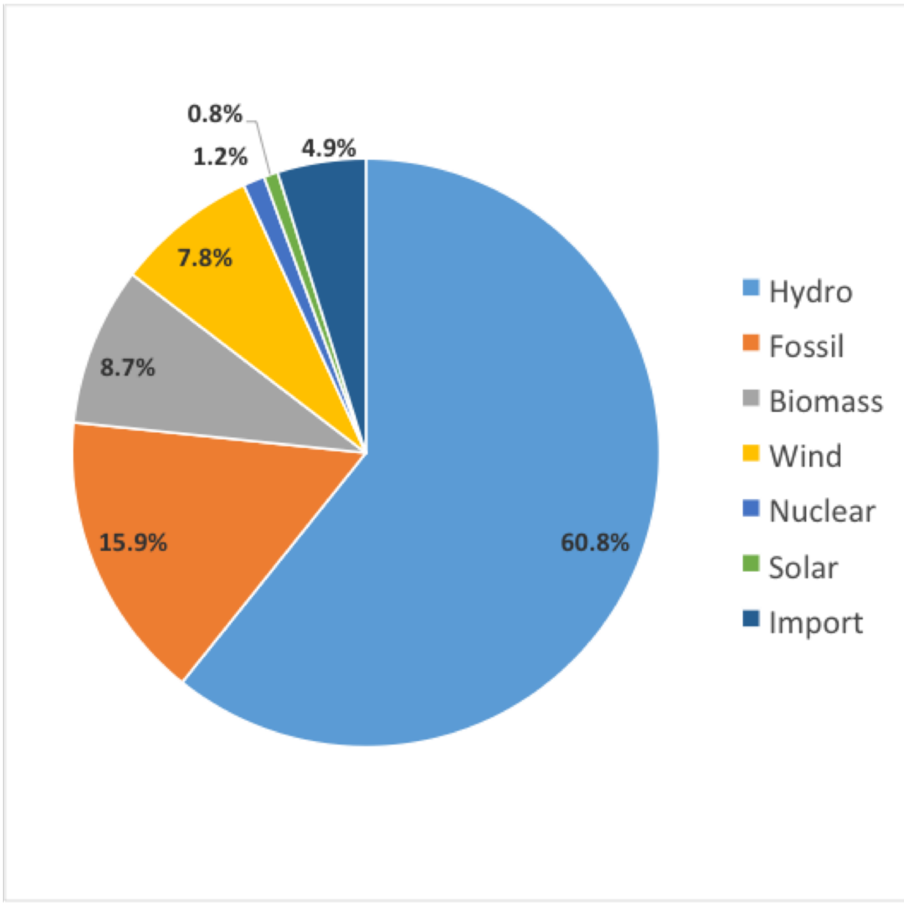

Figure 3 – Brazilian electricity matrix (ANEEL, 2018)

and small hydropower plants (Pereira et al., 2012; Aquila et al., 2017). PROINFA was proposed as an adapted form of feed-in tariff, as it had pre-determined capacities to be commercialized for each source. In its first phase (which took place in 2004), for each source, 1100 MW of energy would be commercialized at a subsidized price given the different investment needs. However, the set price for sugarcane bagasse of $47.55 /MWh was not attractive for some producers, which led to the trade of only 685 MW out of the 1100MW firstly predicted (Dutra and Szklo, 2008). In fact, Grisi et al. (2012) argue that PROINFA's price for sugarcane bagasse was lower than the opportunity costs for electricity in this industry, evidencing the shortened result obtained.

Following PROINFA's short outcome for the biomass sources, new public policies were implemented to incentivize clean sources of energy and reduce the GHG emissions. For biomass sources, for instance, some incentive actions that are in practice are: a reduction on the tariff applied for distribution/transmission of electricity, incentives to auto-production and distributed generation, and special auctions destined to Alternative

Sources (in Portuguese, Leilões de Fontes Alternativas). The outcome of those policies is reflected on the Brazilian matrix presented in Fig. 3 , in which biomass is currently the third most relevant source in terms of installed capacity.

These series of reforms and incentive policies (Araújo et al., 2008; Pereira et al, 2012) implemented in the past 30 years have encouraged many sugarcane producers to invest in technologies to improve their generation efficiency, and now sugarcane mills hold about 7% of the national installed capacity for electricity supply. Albeit significant, this share is still far from the industry's potential, which is estimated to be around 18% of the Brazilian matrix if the biomass residues are entirely utilized for energy purposes (UNICA, 2018).

There are several technologies to increase generation capacity in sugarcane mills, which are promising although cost-intensive alternatives. Despite of the opportunity for growth, however, new bioenergy projects have suffered a significant decrease in numbers over the past 10 years. Thus, given the important role played by the sugarcane sector in the energy matrix, and the still existent need for governmental policies to incentivize renewable and reliable sources, it is paramount to address the challenges that hinder bioenergy generation. The perspectives on technological routes and a thorough discussion on the difficulties in attracting new investments on bioenergy projects will be presented in detail in Section 2.2.

2.2 Perspectives on bioenergy generation

2.2.1 Applications of sugarcane bagasse

Driven by the increasing economic value of bioelectricity in the Brazilian market, several studies have assessed prospective technological routes to improve the efficiency of energy recovery from bagasse, the main residue in the industry.

Ensinas et al. (2007) apply simulation methods to analyze the steam demand reduction in sugar and ethanol processes and alternatives for cogeneration systems in sugarcane plants. The authors evaluate four configurations of cogeneration: traditional Rankine (steam) cycle with a back-pressure turbine, a steam cycle with extraction-condensation turbine, and two configurations based on biomass gasification. All scenarios were performed using a fixed 50%-share of juice for both sugar and ethanol processes. Evidences show that steam cycles with condensation-extraction turbines provide a considerable increase on surplus electricity generation in plants with reduced steam demand. Another advantage of this cogeneration system is that it provides higher flexibility to power generation, including the possibility of production in non-crushing months. In the case of traditional Rankine cycles, the sugar process determines the quantity of steam that can be produced by the boiler, since there is not a condensation system, thus being able to operate only during crushing season (Ensimas et al, 2007).

Dantas et al. (2013) discuss the costs of 3 investment options that allow a more efficient use of bagasse: increase in power capacity through condensing-extraction of steam in a Rankine cycle based system, a system of combined cycle turbines using syngas from bagasse, and the use of bagasse for second generation ethanol. Similarly to Ensimas et al (2007), the authors also argue in favour of Rankine Cycles with condensation turbines for power generation as the most cost-effective technological route, even though the use of bagasse for ethanol 2G has been broadly discussed in literature as a potential competition for investments in bioelectricity generation (Furlan et al, 2012; Hofsetz and Silva, 2012).

Dias et al. (2013) evaluated a flexible biorefinery in which lignocellulosic material (bagasse and trash) could be used both for bioelectricity and second generation ethanol. Three scenarios for the technological routes were evaluated in the study: 1G2G(+ethanol) production, with maximum ethanol production as all surplus bagasse is used for ethanol 2G; 1G2G (+electricity), in which approximately 50% of the surplus bagasse used as feedstock in the first scenario is diverted to electricity generation, and 1G2G (flex), in which there is a flexibility in the use of the lignocellulosic material given the market conditions in each season. In the latter two scenarios, it was considered that a condensation-turbine was also implemented, while in the first scenario the traditional Rankine cycle with the back-pressure turbine is used. Results show that the flexible biorefinery presents a better financial outcome, even though the three scenarios suggested a great sensitivity to changes in ethanol prices. That is, according to the study, an increase in prices practiced for ethanol in Brazil would make the 1G2G (+ethanol) scenario more advantageous.

Despite the large number of studies in literature arguing in favor of the ethanol 2G technological route, it is still not considered to be an economically feasible process in industrial scale. Nevertheless, recent studies started assessing potential applications of other residues from the industry for energy purposes, which could affect the use of bagasse. This is the case of biogas generation from vinasse, for which the energy potential is said to be comparable to the exceeding energy from cogeneration systems, and thus could even stimulate 2G ethanol production by increasing the availability of surplus bagasse currently used for internal demands of steam and power for the process (Moraes et al, 2014). Actually, the additional revenue from the surplus bagasse resultant from biogas' use as an alternative fuel to supply the internal demand for power would alone make the investment feasible, as evidenced by a recent study (Pazuch et al, 2017). The potential of biogas generation from vinasse will be further discussed in Section 2.2.2.

Finally, as far as technological routes for bagasse are concerned, in general studies support the economically feasibility of improving efficiency in the use of bagasse for energy purposes. Controversially, the scenario of decrease in new investments evidences that there are some important drawbacks that were not considered in previous works in the literature. Those challenges in attracting new investments on bioenergy generation will be discussed later on in this work.

2.2.2 The potential of biogas production from vinasse

In the previous sections, vinasse was pointed as a problematic and significant residue in the sugarcane industry. As the ethanol production in Brazil increased, placing the country as second largest producer in the world (FAO, 2019), there was a need to find a proper destination for the resultant vinasse, since for every litter of ethanol produced, an average of 12 litters of vinasse is generated (Leme and Seabra, 2017).

Currently, producers broadly use vinasse as a fertilizer. However, although this is a practice in accordance with environmental regulations in Brazil at present days, studies evidence several negative effects of the direct application of untreated vinasse on the soil. Christofoletti et al (2013) examine the environmental implications of its use. Although the authors argue that fertirrigation is among the best alternatives for vinasse disposal, they highlight the possible long-term implications in the chemical and physical-chemical properties of the soil, rivers, and lakes with frequent discharges over an extensive period of time, as well as the potential contamination of underground water.

Thus, the economic and technical feasibility of biogas generation from vinasse has been subject to on-going research. Salomon et al. (2011) estimated the investment costs of and evaluated four possible applications of the resultant gas for energy generation purposes. They pointed out electric power generation with reciprocating combustion engines (RCE) as the best technological route for power generation with biogas and highlighted that its use for power commercialization is economically feasible under the cost scenarios presented.

Moraes et al (2014) discusses the technical, economic and environmental feasibility of vinasse's use for biogas production, arguing that the technology diffusion is retarded by "*the lack of valorization of biogas as an alternative fuel and the successful diffusion of fertirrigation, which is not currently subject to appropriate environmental control*" (Moraes et al, 2014). The study assessed the biogas application as diesel substitute for transportation efforts in the sugarcane sector, its use for cogeneration and electric energy generation in stationary internal combustion engines. Although it is still not technically viable due to the lack of engines adapted for biogas in this sector, fuel substitution was pointed as the best alternative both from the economic and the environmental point of view, in the scenario conditions of the study. In addition, the paper compares the vinasse potential for energy production to the electricity consumption of some cities in Brazil, and highlights the environmental positive effects of previous biodigestion of the vinasse later sent to fertirrigation. The overall conclusions are that biogas production from vinasse would potentially lead to greater profits in the industry.

Other recent studies still address the economic feasibility of biogas production from sugarcane vinasse in Brazil, as it is still an incipient activity with only 8 out of the distilleries in the State of São Paulo employing alternative processes for vinasse's use (Bernal et al, 2017). Pazuch et al (2017) analyses the potential use of biogas as a substitute for bagasse in power generation. The results evidence that, in the particular case study performed, the additional revenue from selling the surplus bagasse that would be freed if biogas was used to supply the internal power demand could already make this investment viable.

Leme and Seabra (2017) assessed the different technological routes for biogas production in sugarcane mills. Organic-physical scrubbing was pointed as the best alternative in relation to costs. However, the variation range of costs for all technologies assessed was considerably narrow, inducing the authors to conclude that none of them should be discarded as an option. Among the main considerations presented in this study, stand out the breakdown of costs in biogas production, the possible benchmarks for its economic use and the analysis of economic scenarios (including economy of scale) for biogas production. The two costs highlighted were the investment costs, as expected, and the operational costs associated to H_2S removal. The latter, on the other hand, may be an important activity in order to avoid soil contamination with vinasse (Moraes et al, 2014; Leme and Seabra, 2017).

Furthermore, the study presents pipeline natural gas and diesel oil used in transportation as important benchmarks for biogas use. At the cost range of R$31/GJ found in the study, it would be "*competitive with imported Liquified Natural Gas (LNG) as compared to 2013 prices, but not so much if compared with Bolivian natural gas, with a price gap of about 50%*" (Leme and Seabra, 2017). For all technologies considered, biogas' use for diesel substitution in the sugarcane industry would be economic feasible. Additionally, the results also point out a minimal production of biogas to guarantee this feasibility, being in the scale of 87M litters of ethanol per season for the application in diesel substitution, and 174 M litters per season for competitive prices to face natural gas.

Bernal et al (2017) also highlight the relevance of biomass availability to the potential returns for biogas's projects, relating the production to areas of sugarcane plantation. The analysis compares scenarios for autonomous plants (that is, a plant that produces only ethanol) and annexed plants (simultaneous production of ethanol and sugar). Results showed that energy potential for autonomous plants is greater than that of the annexed ones. However, for this study, the authors used a share of 50% for ethanol production, and 50% for sugar production. This may not be an accurate assumption, because in several scenarios of this industry, those shares may vary due to market conditions and they are subject to decision-making of producers.

Fig. 4 presents the minimum sugarcane productions against the expected rates of returns for the biogas projects. Clearly, the return grows as the sugarcane production rises, showing a particular advantage for autonomous plants as they require less sugarcane for a given return rate. The authors conclude that the potential energy produced from vinasse biogas may supply 0,52% of the total energy consumption in the country, representing a relevant business opportunity to increase profit and reduce emissions in the sugarcane industry.

On one hand, the discussed studies emphasize the economic feasibility of biogas production from sugarcane vinasse. On the other hand, it is also noted that this is still not an explored activity in present days. Possible reasons for that are the challenges related to biogas commercialization. As pointed out by Moraes et al (2014), one important potential use of biogas as substitute for diesel is still not technically feasible, and selling gas presents some challenges. Biogas has similar characteristics with those of natural gas,

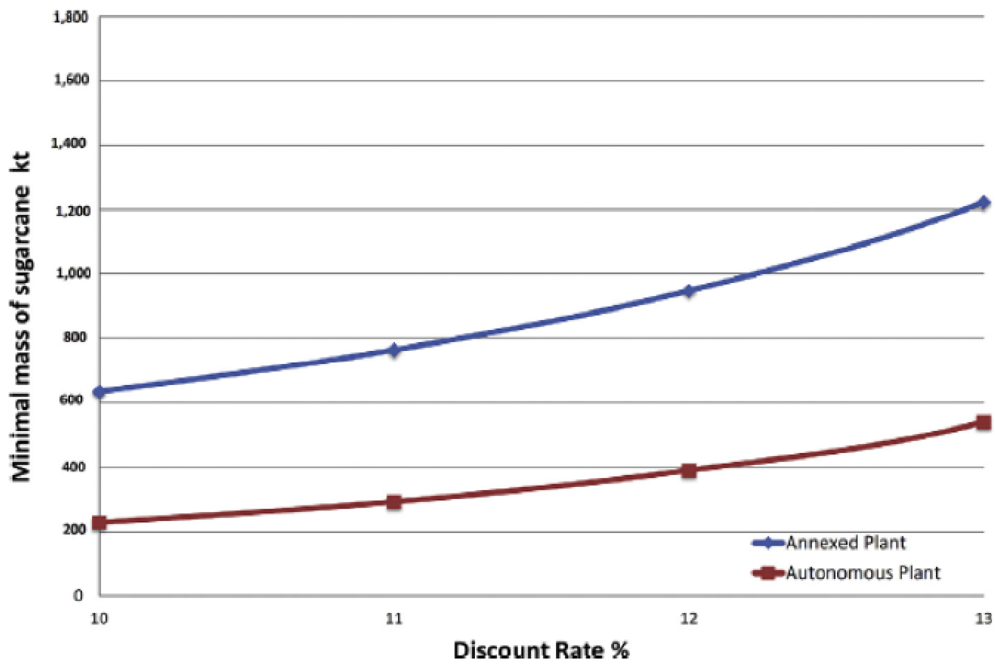

Figure 4 – Minimum mass of milled cane as a function of the discount rate (Bernal et al, 2017)

that is, dedicated assets, and geographical and time specificities, which greatly increase investment risks in gas transportation (Ferraro and Hallack, 2012). As gas pipelines are not vastly available in Brazil, this may be a relevant barrier for biogas production in large scale. Ferraro and Hallack (2012) analyse recent public policies to incentive private investments for gas in Brazil. Nevertheless, the authors note that the difficulties in reaching the distribution channels may discourage investors in transportation and production.

Similarly to the case of bagasse, technological routes to produce energy from vinasse are also shown to be promising opportunities for sugarcane producers, but do not reflect the current market scenario. Particularly in the case of biogas generation, the challenges are even greater, as now logistic and infrastructure aspects shall be also taken into account. Thus, given the relevance of finding environmentally friendly uses for vinasse, and also the potential of biogas as an energy source, those additional challenges shall be addressed in this work and will be further discussed in Chapter 3.

2.2.3 The challenges in attracting investments on bioenergy generation

In spite of the large number of new technologies available to increase energy recovery from residues, and the several analyses supporting their economic feasibility, the Brazilian sugarcane industry currently suffers a reduction in investments on bioenergy generation. The addition of new installed capacity of bioelectricity in 2018 was estimated to be only 132 MW, following a decrease on capacity insertion from biomass sources over the past years, falling from as high as 32% of the total capacity added to the matrix in 2009, to 7% in 2017 and 0% in 2019 (UNICA, 2018). In comparison with other sources, for example, biomass presents a significant lower capacity insertion among the years 2017 and 2019. The surprising inexistence of new projects of bioelectricity is a relevant evidence of the need for new public policies to incentivize investments on power generation by this source.

Historically, energy generation projects in the sugarcane sector have been highly influenced by governmental interference. However, some authors argue that Brazilian policymakers may have not yet fully found the formula to incentivize power generation in mills (Hofsetz and Silva, 2012). This is because deciding on price policies for bioelectricity is a challenge. From the producers' point of view, their main focus is on the sugar-ethanol business, thus market conditions must be really promising in order to attract their attention for new bioenergy technologies. Furthermore, there are some key sources of difficulties in the decision-making process that will be discussed below.

First of all, new bioenergy projects change the process conditions in the sugarcane mills and thus it is mandatory to perform a thorough analysis prior to making investments in order to guarantee feasibility. In the case of the sugarcane industry, the first-generation processes for sugar and ethanol production seem to have reached their state-of-the-art (Castro et al, 2018). On the other hand, there has been an on-going research effort towards new processes to increase energy recovery from the biomass waste generated in large-scale in this sector, which imply complex problems regarding feasibility of the resultant combined processes. The implementation of bioenergy generation processes impact the overall energy balance of the sugarcane mill, and thus must be seen as integrated systems with the first-generation processes. In a sugarcane plant with annexed biorefinery, in which sugar and ethanol are produced simultaneously, steam consumption is highly dependent on the industrial mix for those two products, consequently impacting the availability of biomass for energy generation purposes.

Secondly, price risks play a major role in the decision-making process, especially when the producer faces cost-intensive investment alternatives. Production decisions in the sugarcane sector mainly involve the use of resources so that the economic results are maximized during the annual season. Traditionally, the most important product mix decisions are the shares of sugar and ethanol productions, since those have been historically volatile. In fact, the relevance of price variations in this sector is clearly seen in Fig. 5, in which historical price records of sugar, ethanol and spot market electricity are presented at a weekly frequency between 2002 and 2018. Notice that, in addition to variations within one annual season, the behaviour of the market changes also among years in the historical series. Those variations may be caused by several aspects of the market, including climate conditions, crop failures in other producing countries and changes in the general economic scenarios.

Thirdly, an important decision to make in parallel with investments for capacity insertion is where to sell the surplus electricity available. In Brazil, there are two environments for power sales: the free market, which is subject to significant price variations, and the regulated market, in which prices are fixed for 20 to 25-years-long contracts. Sugarcane producers have to decide to what market they will destine their surplus power, since they present significantly different conditions. Especially in the case of spot market electricity, it is paramount to consider those price variations when facing investment opportunities to increase energy generation. Decisions based only on expected price scenarios lead investors to make risk-inclined decisions, potentially causing shortfalls. Nevertheless, in this context, power sales to the regulated market may be a strategy to reduce the potential variation in revenue during the annual season, as diversification is broadly seen in finance as a strategy to mitigate risks (Markowitz, 1952).

Accordingly, new technological routes are usually made feasible in the regulated market, since the risks are reduced given that prices are fixed in long-term contracts. Nevertheless, the current scenario shows a tendency for producers to sell their existing surplus electricity in the free market, as today about 64% of bioelectricity generation to the BESI is commercialized mainly through bilateral short-to-mid-term contracts (UNICA, 2018). This may evidence the still existent difficulty in setting attractive prices for bioenergy in the regulated environment, although it clearly presents an advantage in regards of

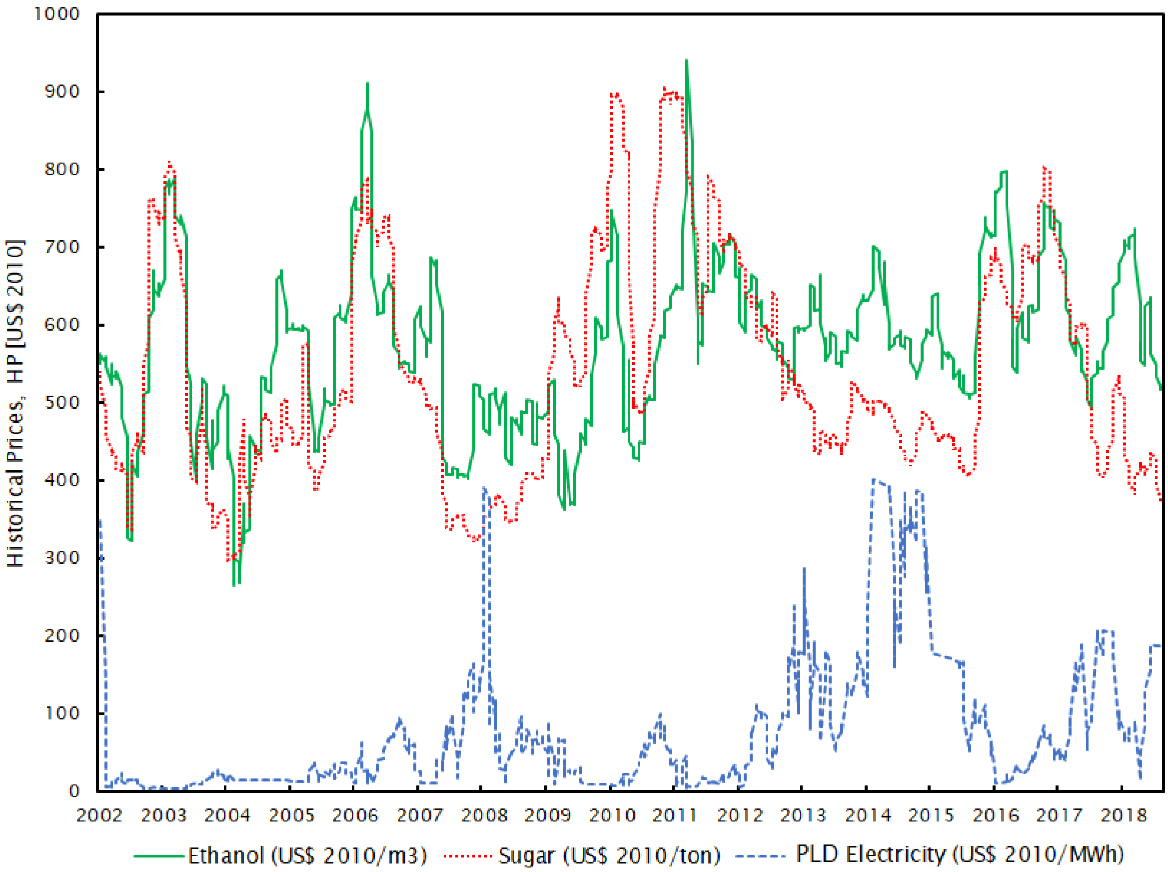

Figure 5 – Historical Price records of sugar, ethanol and free market electricity (Source: Bloomberg, 2018).

risk reduction, especially for price volatility and revenue. Hence, given the important role of the sugarcane industry as an environmentally friendly alternative for fossil-fuelled thermoelectric plants, it is relevant to develop a method to assist price policy making in order to be more attractive to new investors.

In turn, from the policymaker point of view, the biggest challenge is to set attractive prices for this source, given the broad range of investment options that sugarcane producers have, including activities other than bioenergy generation. Along theses lines, the Brazilian government has already tried different approaches over the years. There are three main strategies to incentivize Renewable Energy Sources (RES) in the long-term: feed-in tariffs, auctions, and the quota system (Aquila et al., 2017). The first big step for investments in new sources in Brazil, PROINFA, is classified as a feed-in-tariff policy. In general, those strategies have been efficient policies for incentives in RES' new generation (Liao et al., 2011; Aquila et al., 2017), but PROINFA was not successful in attracting the expected investments for biomass due to miscalculated price policies.

Subsequently, in light of a second important electricity reform implemented in the early 2000s, the RES's incentive programs were also restructured. The second phase of PROINFA, for example, no longer followed the feed-in tariff strategy. Actually, it was adapted to the auction-based model, as all other trades in the sector (Aquila et al., 2017). The subsequent actions to attract renewable energy generators were also through specific auctions for each source, in such a way that allowed competitiveness for those with greater investment costs. For this strategy of incentives through source-specific auctions, setting an attractive price is also an important challenge, as pointed out by Rego and Parente (2013). The authors discuss the impact of inadequate prices practiced in Brazilian energy auctions, evidencing that erroneous price caps may lead to lack of interest from new investors. This is an important issue, especially in the case of bioenergy generation from sugarcane mills, as the producers have several alternatives for the use of their biomass.

Grisi et al. (2012) compared the price practiced in PROINFA's first phase with the ones set for auctions of renewable energy in 2008 and 2009, evidencing that the latter were more accurate with the opportunity cost of bioenergy generation. The authors developed an optimization model to decide the product mix that maximized profits in a sugarcane mill, and argued that power sales to the regulated market played a major part in the profits of the mill. Nevertheless, the analysis did not account for risks, which as previously argued plays an important role in the decision-making process for power sales.

Recent studies have proposed risk-conscious models to make product mix decisions in the sugarcane sector. Carpio and Souza (2017) proposed an optimization model based on the Modern Portfolio Theory to find the optimal distribution for the use of surplus bagasse in sugarcane mills: selling in the free market, in the regulated market and its use for the production of second generation ethanol. Dutenkefer et al (2018) developed a robust portfolio optimization model to assess the insertion of biogas into the product mix of sugarcane mills, while Oliveira et al (2018) applied portfolio optimization to decide on hedging strategies for sugar and ethanol, including also storage decisions throughout the season.

None of the above-mentioned studies took into account technological routes for investments, which is among the main objectives of the present work. In addition, they all assumed a fixed amount of surplus bagasse available each season. In practice, this means that the decisions regarding the use of bagasse for energy generation was considered to be independent from the production decisions for sugar and ethanol. Based on the literature discussed in the previous sections, we argue that those decisions must be concomitant, especially when assessing new energy generation processes that may affect the overall conditions of the plant.

Therefore, considering the limitations of previous studies in literature, this project proposes to develop an optimization framework to allow the assessment of new bioenergy projects in light of the relevant price risks associated to all products in the industry, as well as the production-dependent conditions that determine the availability of biomass for surplus energy purposes. In the next section, relevant literature on optimization methods will be discussed to support the model development.

2.3 Optimization methods

In this section, relevant optimization methods from the literature will be discussed. The modelling approaches presented here will be used as foundations for the development of the model proposed in this project, which will be further detailed in Chapter 3.

2.3.1 Portfolio theory

Risk is a well-established concept in literature, which is generally associated to the probability of negative outcomes, damages, or losses. The idea of risk exists when a certain event is subject to uncertainty, that is, when the result of an action is not deterministic.

In finance, risk is defined as the probability that the realization of the return of an investment is less than its expected value. Given that the investors' main goal is to maximize returns, it is paramount to use risk-conscious decision-making approaches in order to minimize potential shortfalls. The portfolio selection theory was developed by Markowitz (1952) as a method to optimize the selection of assets for a portfolio of investments. The model proposed portfolio diversification as a strategy for reduction in investment risks, in which the author considered a trade-off between expected return and risks to build an efficient frontier for portfolios.

Markowitz's original model uses variance (σ^2) as a risk-measure. Let $x \in IR^n$ be a decision vector that corresponds to the percentage of each asset in a portfolio, and $r \in IR^n$ the vector of the respective expected returns of each one of those assets. Thus, the overall expected return of the portfolio for a given x is expressed by $r^T x$. Further, let $\Omega \in IR^{n*n}$ be the covariance matrix of the returns of the assets. Finally, the portfolio optimization model is given by,

$$\min \sigma^2 = x^T \Omega x \tag{1}$$

$$s.t. \quad r^T x \geq R_0 \tag{2}$$

$$\sum_{i=1}^{n} x_i = 1 \tag{3}$$

where R_0 is a pre-defined mininum expected return for the portfolio. The mean-variance portfolio problem, based on Markowitz (1952), has been vastly used for optimization in literature for several different applications. Hultman (2006) uses the portfolio theory to address the carbon financial risk by geographic diversification. Paydar and Qureshi (2012) applied the method for water management in the agricultural sector. Francés et al (2013) used the approach to analyse the contribution of renewable energy sources to reduce risks in electricity supply. Recently, Costa et al (2017) developed a robust optimization model for the portfolio decisions applied to the Brazilian electricity sector, considering both the expected costs and the covariance matrix for different technologies to belong to uncertainty sets.

Although the portfolio optimization model (Markowitz, 1952) has been successfully applied in several sectors, the use of variance as a measure of risk implies an inconvenient in some applications as it penalizes identically negative and positive deviations. In the case of the sugarcane industry, where gains in profitability should not be discarded, Markowitz's model may not be the most adequate approach.

Thereupon, Rockafellar and Uryasev (2000) proposed a model that presents an asymmetric measure, the Conditional Value at Risk (CVaR). CVaR is a single-tail measure that accounts for the losses at a limited percentile β. The description of the CVaR approach as formulated by Rockafellar and Uryasev (2000) is presented below.

Let $f(x, y)$ be a loss function associated with x, a decision vector, and y, a random vector, such that $x \in IR^n$, $y \in IR^m$. For every x, the loss $f(x, y)$ is a random variable with domain in IR generated by the distribution of y. Further, let $p(y)$ be the probability distribution of $y \in IR^m$, therefore the function $\Psi(x, \alpha)$ is defined as the probability of the function $f(x, y)$ not exceeding the limit α, with $\alpha \in IR$. This can be stated as,

$$\Psi(x, \alpha) = \int_{f(x,y) \leq \alpha} p(y)dy \tag{4}$$

For a given vector x, $\Psi(x, \alpha)$ as a function of α may be interpreted as a function of the cumulative distribution of the loss associated with x. Although in general $\Psi(x, \alpha)$ with respect to α may present jumps from the left side, it will be assumed that no jumps occur, so the function is everywhere continuous with respect to α. For any specified probability level $\beta \in (0, 1)$, the value at risk at level β, $\alpha_\beta(x)$, and the conditional value at risk at level β, $\phi_\beta(x)$, may be stated as,

$$\alpha_\beta(x) = \min\{\alpha \in IR; \Psi(x, \alpha) \geq \beta\} \tag{5}$$

$$\phi_\beta(x) = \frac{1}{1-\beta} \int_{f(x,y) \geq \alpha_\beta(x)} f(x, y)p(y)dy \tag{6}$$

In order to restate the problem in a treatable manner, Rockafellar and Uryasev (2000) proposed the following auxiliary function,

$$F_\beta(x, \alpha) = \alpha + \frac{1}{1-\beta} \int_{y \in IR^m} [f(x, y) - \alpha]^+ p(y)dy \tag{7}$$

where $[t]^+ = t$, when $t > 0$, but $[t]^+ = 0$, when $t \leq 0$. $F_\beta(x, \alpha)$ as a function of α is proved to be convex and differentiable. In order to obtain an approximation for Eq. 7, the authors propose the discretization of the probability distribution $p(y)$ through Monte Carlo simulations, or through the use of a long historical series of observations. The resulting optimization problem is ammenable to a fully linear formulation. Further, it is also proved that when optimizing the problem for a minimal CVaR, the Value at Risk, and the Variance are simultaneously minimized. Hence, given those key properties of CVaR as a risk measure, it was elected for the formulation of the optimization model proposed in this work.

2.3.2 Surrogate-based superstructure optimization

Surrogate-based optimization models have been broadly used in literature as a promising alternative for solving optimization problems that are computationally intensive, as this technique implicates speeding the optimization process by the use of "surrogates".

According to Wang et al (2014), surrogates are generally statistical regression methods that estimate the response surface of a simulation model.

Queipo et al (2005) and Forrester and Keane (2009) presented a description of the steps for surrogate construction, analysis and optimization. According to the authors, the method has been successfully applied in aerospace modelling, an area in which complexities of models are fairly high.

Recently, surrogate-based superstructure optimization has become a common approach for optimization in chemical processes. Henao and Maravelias (2011) presented a comprehensive methodology for this framework to be applied in several cases of chemical engineering. Furlan et al (2012) assessed the use of bagasse in a sugarcane mill, considering its possible destination for second-generation ethanol, steam production, electricity generation, and commercialization of the surplus. The study proposed a tool that jointed global optimization with the detailed modelling and simulation of the whole integrated biorefinery. Another interesting study applied the surrogate-based superstructure optimization approach to find the best technological routes to be applied for nutrient and energy recovery in wastewater facilities.

In this methodology, similarly to that proposed by Furlan et al (2012), simulations provide input data for a simplified optimization model. After the optimization, the decision variables are fed back into the simulation for validation.

The previously reviewed works on surrogate-based optimization indicate that this approach can be an interesting alternative in the development for the sugarcane portfolio optimization model, which will be discussed in more detail in Chapter 3.

3 Research Approach and Metholodogy

Mitroff et al (1974) proposed a method in their seminal work for the development of optimization models in Operations Research, consisting of a four phases:

- **Conceptualization:** conceptual model in study is developed, with the choice of scope and variables to be considered;
- **Modeling:** Building of the quantitative model, with causal relations between variables;
- **Model solving:** Mathematical evaluation of the developed model;
- **Implementation:** The model is implemented in a practical application.

Their approach is considered in literature as a very helpful tool to identify a methodological path in quantitative model-based research (Bertrand and Fransoo, 2002). Thus, it was used as a basis for the development of the optimization framework proposed in this Thesis.

In the following sections, the model development process will be presented in the form of those four phases, for which each step consisted of a Research Article from the collection that compose this work.

3.1 Conceptualization

In this first phase of the research process, the goal is to understand the dynamics of the sector and identify the main variables in the decision-making for production and investments in a sugarcane mill.

A combination of literature review and qualitative research is therefore proposed to investigate what perspectives decision-makers have on the future of the sector, and what are the drivers and/or factors that lead their short, mid, and long-term decisions.

The comprehensive literature review allowed the identification of past dynamics that affected the sector, at the same time that it enabled the construction of some hypothesis for the concepts of the model. The qualitative research, in turn, is exploratory by nature and therefore enabled an examination of opinions, attitudes and perceptions (Sovacool et al, 2018).

This conceptualization phase involved the following steps:

- An extensive literature review on the Brazilian Sugarcane Industry.
- Data collection from the sector, including historical series on production, commercialization of products, prices, number and location of sugarcane mills, shares of energy matrix, exports, etc.
- Analysis of past dynamics based on the literature and on historical data.
- Development of hypothesis on future perspectives of the sector.
- Identification of main products to be discussed in the interviews (sugar, ethanol, bioelectricity and biogas).
- Creation of prompt sheets of questions for the interviews.
- Selection of interviewees using a purposive sampling strategy, wherein organizations and individuals with expertise on sugarcane were identified and contacted.
- To perform interviews, transcribe recordings and analyse data.
- To identify scope and variables of optimization models.

Seventeen semi-structured interviews were conducted with stakeholders from the sugarcane and energy sectors, whose occupation spanned industry (5), academia (6), government policy maker (5), government policy advisor (1), NGOs (1) and finance (1).

The interviews were structured in two parts. Firstly, participants were asked to reflect on the main economic, technical and policy drivers affecting the Brazilian sugarcane sector since the 1970s. Having discussed the past, participants were asked to think about the short (i.e. to 2025), mid (i.e. to 2030) and longer-term (i.e. beyond 2030) future of the sector and to indicate in a table whether they thought there would be an increase, decrease, no change or no activity, in the sector as a whole, and in relation to the four products of interest to this study: sugar, ethanol, bioelectricity and biogas. In a small number of cases, interviewees chose not to indicate a projection for some products, as they preferred to focus on their area of expertise. Fig. 6 shows the interview template used.

The qualitative research on the sector enabled a better understanding of the dynamics of the decision-making processes for both policymakers and sugarcane producers. Thus, the results obtained in this phase were used as the basis for the development of the optimization framework discussed in the following sections.

	Whole sector	Sugar	Ethanol	Electricity	Biogas
Short-term (2025)					
Mid-term (2030)					
Long-term (beyond 2030)					

↑ = increased activity; ↓ = decreased activity; → = no change; 0 = no activity at all

Figure 6 – Interview Template. (Source: Hughes et al, 2020)

3.2 Modeling

A process superstructure is a representation of the alternatives involved in a decision-making problem (Bertran et al, 2017). Superstructure modelling for optimization is a well-developed approach in process systems engineering, which has been successfully applied to a broad range of process synthesis and design problems, including several kinds of biorefineries (Zondervan et al, 2011; Eason and Cremaschi, 2014; Cheng and Anderson, 2016), technological routes to improve energy recovery from waste (Puchongkawarin et al, 2014), and even biomass use in the sugarcane sector (Bechara et al, 2016; Fonseca et al, 2017).

The use of superstructures is an interesting approach to address process design problems because it allows a comprehensive optimization of both the process configuration and operation conditions. However, this usually comes at the price of increasing complexity of the mathematical models (Henao and Maravelias, 2011). Thus, an alternative modeling technique to reduce the difficulty in solving such types of optimization problems is the use of process simulation to build surrogates, that is, representative approximations of the real process models.

Particularly in the case of the sugarcane industry, the first-generation processes for sugar and ethanol production seem to have reached their state-of-the-art (Castro et al, 2018). On the other hand, there has been an on-going research effort towards new processes to increase energy recovery from the biomass waste generated in large-scale in this sector, which imply complex problems regarding feasibility of the resultant combined processes. The implementation of new bioenergy generation processes impact the overall energy balance of the sugarcane mill, and thus must be seen as integrated systems with the first-generation plants. As previously discussed, in a sugarcane plant with annexed biorefinery, in which sugar and ethanol are produced simultaneously, steam consumption is highly dependent on the industrial mix for those two products, consequently impacting the availability of biomass for energy generation purposes.

One could argue that a natural approach would be to model the steam utility as part of the process. Nevertheless, there are several streams of recycling of steam varying with production mixes and explicitly modelling those steam flows would significantly increase the complexity of the mathematical formulation.

This recently motivated the development of the Open Sugarcane Process Simulation Platform, an easy and simple computational platform implemented in Matlab which was developed with the aims of providing reliable process parameters for the economic assessment of bioenergy projects in sugarcane mills (Castro et al, 2018). In this project, it is proposed to use this process simulator to derive process performance data, later used to build surrogates that approximate the overall surplus bagasse and power generation in a sugarcane mill.

Thus, this project's methodological approach for decision-making in the sugarcane industry aims to (i) leverage on a detailed process simulator, and (ii) apply portfolio optimization theory to optimize product mix and assess investment options under market uncertainty. It should be highlighted that a direct optimization based on the process simulator would be computationally intractable, therefore a simplified mass-balance model is considered for the process representation. The portfolio optimization model is then built based on a superstructure composed by the sugarcane first-generation process and the investment alternatives for bioenergy generation.

The proposed optimization framework is presented in Fig. 7. The Open Sugarcane Process Simulation Platform is used to derive the process performances for each product mix scenario, which are then approximated by surrogates and used as inputs to the portfolio optimization model. As a result of this optimization framework, we obtain risk-conscious optimal decisions for annual production mixes and investments on new bioenergy projects.

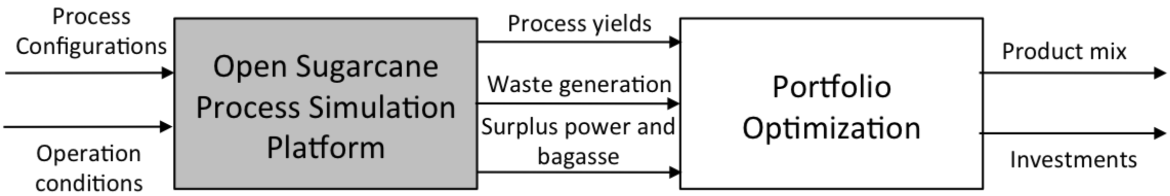

Figure 7 – The proposed surrogate-based optimization framework

3.2.1 Sugarcane plantwide modeling

The sugarcane process models are herein expressed in generic mass-conversation equations, which are applied to all mills $u \in U = \{1, \dots, M\}$, where M is the number of mills in an interacting group. A first key assumption in the model is about the fixed amount of sugarcane, Ca_u, that is available for crushing during each season at mill u. Yearly variations in sugarcane productivity can be as much as 10% due to the local climatic conditions (UNICA[b], 2018) but producers are usually well-aware of the average sugarcane production of their plantations. Thus, we have that,

$$x_{cane,u} = Ca_u \tag{8}$$

where $x_{j,u}$ is a continuous variable that denotes the total amount of product j available in mill u for that annual season.

For each sugarcane mill, process decisions generally regard the use of resources that provide the best economic outcome in the end of the annual season. Table 2 presents the sets of mills, products and by-products considered in the model.

Set	**Description**
U	{1,. . . ,M}, set of mills in the interacting group
J	{cane, jui, bag, mol, vin, bio, el, el-r, el-c, el-b, meth, sug, eth, fert, free, reg, fuel, surp}, set of products and by-products in mill $u \in U$
I	{cane, jui, bag, mol, vin, bio, el, el-r, el-c, el-b}, set of resources in mill $u \in U$
L	{ sug, eth, fert, free,reg, meth, fuel, surp}, set of saleable products in mill $u \in U$

Table 2 – Model sets

Let $r_{i,j,u}$ be a decision variable that denotes a production decision for the use of resource i to be destined to the production of product j in mill u. Thus, given a pre-existent process configuration in each mill u, and potential technological routes to be implemented, all production decisions are subject to a maximum processing installed capacity.

$$r_{i,j,u} \leq G_{i,j,u} z_{i,j,u} \tag{9}$$

where $z_{i,j,u} \in \{0, N_{i,j,u}\}$ is an integer variable which defines the number of parallel processing units used to produce product j from resource i at mill u, with $N_{i,j,u} \geq 1$ the maximum number of units; and $G_{i,j,u}$ is the annual capacity of one processing unit.

The first step is the milling process, for the extraction of sugarcane juice (Eq. 10):

$$x_{jui,u} = \gamma_{cane,jui,u} x_{cane,u} \tag{10}$$

where $\gamma_{j,i,u}$ is a parameter denoting the yield of resource i from product j in mill u. The fibrous residue from this extraction process is the sugarcane bagasse, which is broadly used in Combined Heat and Power (CHP) systems, and will be further discussed later on.

The main decision producers face each season is the share of sugarcane juice that will be used for sugar and ethanol productions in each mill. This is usually based on the market conditions in the beginning of the crop, and also on their perception of price risks (Eq.11).

$$x_{jui,u} = r_{jui,sug,u} + r_{jui,eth,u} \tag{11}$$

In the sugar factory, there is the production of sugar (Eq. 12) and the generation of a by-product, the molasses (Eq. 13), that is later used as a resource in the ethanol production (Eq. 14):

$$x_{sug,u} = \theta_{jui,sug,u} r_{jui,sug,u} \tag{12}$$

$$x_{mol,u} = \gamma_{sug,mol,u} x_{sug,u} \tag{13}$$

$$x_{mol,u} = r_{mol,eth,u} \tag{14}$$

where $\theta_{i,j,u}$ is the process conversion rate from resource i into product j in mill u.

In the distillery, ethanol can be produced with juice, molasses or, as per a more recent technology, with the sugarcane bagasse, in the second generation ethanol process (Eq. 15):

$$x_{eth,u} = \theta_{jui,eth,u} r_{jui,eth,u} + \theta_{mol,eth,u} r_{mol,eth,u} + \theta_{bag,eth,u} r_{bag,eth,u} \tag{15}$$

The bottom product of the distillation process is the vinasse (Eq. 16) , a problematic residue that is broadly used as a fertilizer in the sugarcane fields, but more recently has been applied to biogas generation:

$$x_{vin,u} = \gamma_{eth,vin,u} x_{eth,u} \tag{16}$$

$$x_{vin,u} = r_{vin,fert,u} + r_{vin,bio,u} \tag{17}$$

$$x_{fert,u} = \theta_{vin,fert,u} r_{vin,fert,u} \tag{18}$$

The biogas can be generated in a sugarcane mill either from vinasse and bagasse (Eq. 19) and it has three potential applications: (i) for the production of biomethane to be commercialized and distributed through pipelines, (ii) to be used as a fuel for the trucks in the sugarcane fields, or (iii) for the generation of electricity (Eq. 20-21).

$$x_{bio,u} = \theta_{vin,bio,u} r_{vin,bio,u} + \theta_{bag,bio,u} r_{bag,bio,u} \tag{19}$$

$$x_{bio,u} = r_{bio,meth,u} + r_{bio,fuel,u} + r_{bio,el-b,u} \tag{20}$$

$$x_{j,u} = \theta_{bio,j,u} r_{bio,j,u}, \quad j = \{meth, fuel, el-b\} \tag{21}$$

Now, let us discuss the generation, exchange and use of bagasse in the group of sugarcane mills. As previously mentioned, the bagasse is broadly used in sugarcane mills as a fuel in combined heat and power (CHP) processes, which generate thermal and electrical energy for the internal consumption of the plant. Thus, it is assumed that only surplus bagasse can be used for other economic applications, namely the available bagasse after the deduction of the internal demand of the CHP for this resource ($D_{bag,u}$). Another key assumption is that bagasse may be exchanged among sugarcane mills in the interacting group, for which the continuous variable $w_{bag,v,u}$ denotes the total amount of bagasse sent from mill v to mill u in the annual season. Hence, we have that the total annual amount of surplus bagasse available is:

$$x_{bag,u} = x_{cane,u}\gamma_{cane,bag,u} - D_{bag,u} + \sum_{v \neq u} w_{bag,v,u} - \sum_{v \neq u} w_{bag,u,v} \tag{22}$$

The surplus bagasse available has quite a few economic applications. The most common application is selling surplus bagasse to other industries that use them as a fuel in their own CHPs. Although easily implemented, this application is not very profitable. Recently, some more efficiency uses for the bagasse have emerged, but all of them imply significant investment costs. We consider here the three main uses: (i) in a more efficient power generation system, with a condensation turbine, (ii) for biogas generation and (iii) for the production of ethanol 2G.

$$x_{bag,u} = r_{bag,surp,u} + r_{bag,el-c,u} + r_{bag,bio,u} + r_{bag,eth,u} \tag{23}$$

A further complication comes from the internal consumption of bagasse ($D_{bag,u}$), because it is a function of the sugar production. In this model, we propose to represent this non-linear function in a piecewise linear formulation:

$$r_{jui,sug,u} = \left[\hat{p}_u^0 + \sum_{k=1}^{K} \left(\hat{p}_u^k - \hat{p}_u^{k-1}\right) \xi_{k,u}\right] \, Ca_u \, \gamma_{cane,jui,u} \tag{24}$$

$$\xi_{k,u} \geq y_{k,u} \geq \xi_{k+1,u}\,, \quad k = 1 \ldots K-1 \tag{25}$$

where $\hat{p}_u^k$, $k = 0 \ldots K$ are breakpoints representing the fraction of juice sent to the sugar factory in the piecewise linear approximation; $y_{k,u} \in \{0, 1\}$, $k = 1 \ldots K-1$ and $\xi_{k,u} \in [0, 1]$, $k = 1 \ldots K$ are auxiliary binary and continuous variables, respectively, used to identify the correct subinterval. Then, the corresponding bagasse consumption is:

$$D_{bag,u} = \hat{d}_u^0 + \sum_{k=1}^{K} \left(\hat{d}_u^k - \hat{d}_u^{k-1}\right) \xi_k\,, \tag{26}$$

where $\hat{d}_u^k$, $k = 0 \ldots K$ denote the predicted annual bagasse consumption in mill u for each juice fraction breakpoint $\hat{p}_u^k$.

The steam produced in the CHP with the combustion of bagasse passes through turbines for power generation, and is then consumed as thermal energy in the processes of sugar and ethanol. This way, surplus power available for commercialization is also a function of the demand of bagasse, and depends on the configuration of the CHP installed:

$$x_{el-r,u} \leq f(D_{bag,u}) \tag{27}$$

$$x_{el-c,u} \leq g(D_{bag,u}) + \theta_{bag,el-c,u} r_{bag,el-c,u} \tag{28}$$

$$x_{i,u} = r_{i,el,u}, \quad i \in \{el-r, el-c\} \tag{29}$$

The traditional Rankine cycle (el-r) is mutual exclusive with the improved CHP configuration, with the addition of the condensation turbine (el-c). Thus, we have that only one of the two configurations can be used in the mill:

$$1 = z_{el-r,el,u} + z_{el-c,el,u} \tag{30}$$

and the use surplus bagasse for this application is also conditioned to the investment in the condensation turbine:

$$0 = z_{el-c,el,u} - z_{bag,el-c,u} \tag{31}$$

Finally, we have that the surplus power available for commercialization in each mill u is:

$$x_{el,u} = r_{el-r,el,u} + r_{el-c,el,u} + x_{el-b,u} \tag{32}$$

and this surplus electricity can be sold in two markets in Brazil, free and regulated:

$$x_{el,u} = x_{free,u} + x_{reg,u} \tag{33}$$

3.2.2 Sugarcane Portfolio Optimization Model - SUPOM

The goal of the model is to enable risk-conscious decisions regarding annual production planning and investment alternatives. We assume that saleable product prices are the only source of uncertainty, so the optimization model chooses the best production portfolio to maximize profits in the case of detrimental price scenarios. The decisions are, therefore, based on historical records for sugar, ethanol and spot market electricity prices. Such information from past scenarios is used to robustify decisions against potential short-falls, under the assumption that future market conditions will follow a similar pattern of the past price fluctuations.

The conditional-value-at-risk (CVaR) is used as the risk measure in this portfolio optimization model (Rockafellar and Uryasev, 2000; Rockafellar and Uryasev, 2002), because it is a coherent (Artzner et al, 1999) and convex measure of risk, which is amenable to a tractable, fully linear formulation in optimization problems (Rockafellar and Uryasev, 2000). In Figure 8, we see a graphical representation of the CVaR, the VaR (α), and the expected profit (EP) for a sampled profit distribution.

Suppose that $q = 1 \ldots Q$ historical price observations, $HP_{j,q}$ and production costs, $PC_{j,u}$ are available for each saleable product $l \in L$. Further, assume deterministic costs for transportation of resource i from mill u to mill s, $TC_{i,u,s}$, and equivalent annual costs (EAC), $IC_{i,j,u}$ for the investments in processing units (or equipment) to produce product j from resource i in mill u. For a given process configuration and operation, as represented by the variables x, z and w, the profit corresponding to price observation q = 1. . . Q is:

$$P_q = \sum_u \sum_j (HP_{j,q} - PC_j) x_{j,u} - \sum_u \sum_j \sum_i IC_{i,j,u} z_{i,j,u} - \sum_u \sum_s \sum_i TC_{i,u,s} w_{i,u,s} \tag{34}$$

The expected profit is readily calculated as:

$$EP = \frac{1}{Q} \sum_{q=1}^{Q} P_q \tag{35}$$

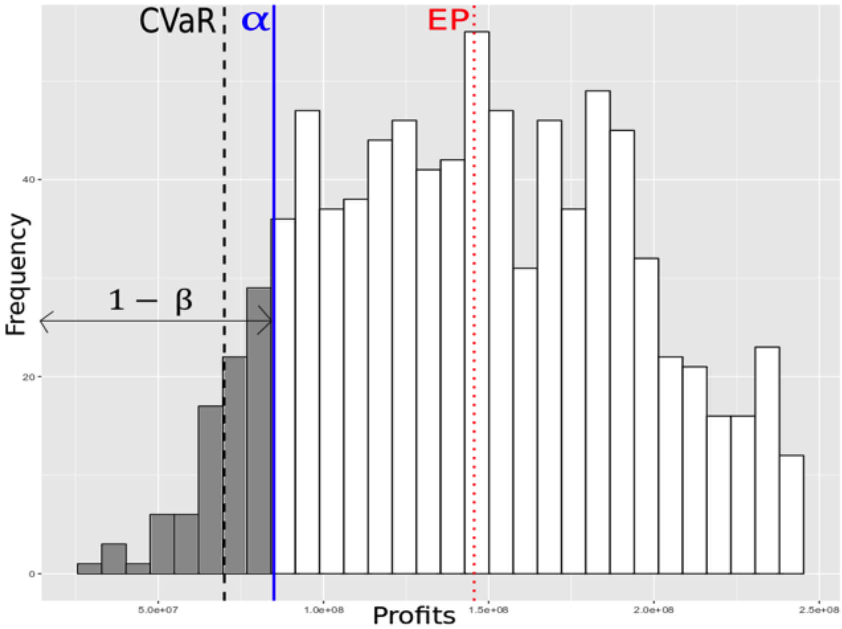

Figure 8 – Graphical depiction of the expected profit (EP), value-at-risk (α) and conditional-value-at-risk (CVaR) for a sampled profit distribution, in connection with the portfolio optimization model (Source: Mutran et al, 2019).

The VaR at a given confidence level β corresponds to the $(1-\beta)$ percentile of the profit distribution, namely the lowest yearly profit after excluding all worse profits whose combined probability is at most $(1-\beta)$. The CVaR, in turn, corresponds to the expected value over all profits lower than the VaR (Fig. 8). It is noteworthy that VaR and CVaR are classically considered loss functions to be minimized in portfolio optimization (right tailed), whereas they are maximized to mitigate risk in the sugarcane portfolio model (left tailed).

Following the optimization approach for CVaR proposed by Rockafellar and Uryasev (2000), the portfolio optimization model for the sugarcane plant superstructure can be stated as:

$$\max_{x,r,w,z,P,S,\alpha} \left\{ \underbrace{\frac{1}{Q}\sum_{q=1}^{Q} P_q}_{\text{EP}},\ \underbrace{\alpha - \frac{1}{Q(1-\beta)}\sum_{q=1}^{Q} S_q}_{\text{CVaR}_\beta} \right\}$$

$$\text{s.t.}\ \ \text{Sugarcane plant model (8)-(33)}$$

$$\forall q = 1 \dots Q,$$

$$\mathrm{S}_q \geq \alpha - P_q$$

$$\mathrm{S}_q \geq 0$$

where α is an auxiliary variable that assumes the value of the VaR when the optimization model is maximized, and S_q are auxiliary variables representing the possible shortfall in each scenario $q = 1 \dots Q$. Note that the problem is bi-objective, seeking a trade-off between the expected profit EP and the risk measure $CVaR_\beta$.

The ϵ-constraint method is applied to construct the Pareto frontier (Miettinen, 1999). First, we solve the problem to maximize $CVaR_\beta$, in order to find the optimal result based solely on risks. Then, the model is solved to maximize EP, to find the best scenario for profits if risks are completely disregarded. With these two results, we have the extreme points of the Pareto frontier, $[EP^{min}, EP^{max}]$.

In order to connect those two points and construct the frontier, we formulate a single-objective optimization problem for one of the objectives, in this case $CVaR_\beta$, and create a constraint for the possible values taken by EP.

$$
\begin{aligned}
\max_{x,r,w,\xi,y,z,P,S,\alpha} \quad & \alpha - \frac{1}{Q(1-\beta)} \sum_{q=1}^{Q} S_q \\
\text{s.t.} \quad & \text{Sugarcane plant model (8)-(33)} \\
& (1/\mathrm{Q}) \textstyle\sum_{q=1}^{Q} P_q \geq \overline{EP} \\
& \forall q = 1 \dots Q, \\
& \mathrm{S}_q \geq \alpha - P_q \\
& \mathrm{S}_q \geq 0
\end{aligned}
$$

Then we solve multiple instances of this optimization problem by varying the parameter $\overline{EP}$ within the extreme points of the Pareto frontier. The resultant optimization problem falls into the class of mixed-integer linear programming (MILP), and can be mathematically computed with the solver CPLEX. Tables 3 and 4 summarize all variables and parameters used in the model.

3.3 Model Solving

In order to solve for the model presented in Section 3.2, an evolutionary approach was proposed, in which we start by solving a simple version of the model and increase complexity step by step.

Research Articles (2-5) were resultant from this model solving process. The steps are described in more details in the following sub-sections. It is noteworthy that some

Variable	Description
$r_{i,j,u}$	use of resource i to produce product j in mill u
$x_{j,u}$	amount of product j in mill u
$w_{bag,v,u}$	amount of bagasse sent from mill v to mill u
$z_{i,j,u}$	integer variable to determine the number of parallel processing units to produce product j from resource i at mill u
α	auxiliary continuous variable in CVaR formulation
S_q	auxiliary variables that represent the shortfall in each scenario q = 1. . . Q
P_q	auxiliary variables that represent profits in each scenario q = 1 . . . Q
$\xi_{k,u}$	auxiliary continuous variable in piecewise linear representation
$\mathrm{y}_{k,u}$	auxiliary binary variable in piecewise linear representation

Table 3 – Model Variables

Parameter	Description
β	confidence level
$\theta_{i,j,u}$	process conversion rate from resource i into product j in mill u
$\gamma_{j,i,u}$	yield of resource i from product j in mill u
Ca_u	yearly amount of sugarcane produced in mill u
$\mathrm{D}_{bag,u}$	internal demand for bagasse at mill u
$\mathrm{G}_{i,j,u}$	annual capacity of processing unit
$\mathrm{N}_{i,j,u}$	maximum number of processing units
K	number of breakpoints in piecewise linear representation
$\hat{p}_u^k$	breakpoint for juice fraction share in piecewise linear formulation
$\hat{d}_u^k$	predicted annual bagasse consumption in mill u for each juice fraction breakpoint $\hat{p}_u^k$
Q	number of historical price observations
$\mathrm{HP}_{j,q}$	price observation q for product j
PC_j	production cost of product j
$\mathrm{IC}_{i,j,u}$	EAC for investment cost of new processing unit
$\mathrm{TC}_{i,u,v}$	transportation cost of resource i from mill u to mill v

Table 4 – Model parameters

adaptations were made in notation to maintain consistency in the present work, thus generating small differences with regards of the original models in the Research Articles.

3.3.1 Single Mill Model: using fixed parameters

The first step in the model solving was a simple, easy to contrive version of the model. The SUPOM was applied to a single sugarcane mill, that is, assuming the set of mills $U = \{1\}$. This means that decision variables ($w_{i,u,s}$) regarding exchange of resources were not considered.

The goal of this first model-based analysis was to gain a better understanding of the role played by price policies on the increase of surplus power generation in the sugarcane sector, while also taking into account the impact of bioelectricity sales on the sugar-ethanol business. Thus, Research Article #2 presents a risk-conscious assessment of an investment decision to increase bioelectricity generation in a single sugarcane mill.

The proposed optimization model is composed by the simplified mass conservation equations to express process conditions (Eq. 8-18), considering the set of products J={cane, jui,bag,mol,vin, sug, eth,fert,free,reg}. Notice that biogas products and byproducts are not considered in this assessment, nor ethanol 2G.

The Open Sugarcane Process Simulation Platform (Castro et al, 2018) was used to simulate process operational conditions and obtain process fixed (deterministic) parameters based on their average yield. The CHP system's models were also simplified, and the assessment of investment options between a traditional Rankine cycle (base-scenario) and a Rankine cycle with a condensation turbine (improved scenario), was done by comparing the average surplus electricity available for commercialization in the sugarcane mill in each configuration:

$$x_{free} + x_{reg} \leq G_{base} z_{base} + G_{imp} z_{imp} \tag{36}$$

$$z_{base} + z_{imp} = 1 \tag{37}$$

where $z_t \in \{0, 1\}$ is the investment decision variable; G_t is a parameter for the annual surplus electricity expected in each configuration $t \in T$ of the cogeneration process, with the set $T = \{base, imp\}$; and the surplus electricity production is separated into free and regulated market sales, which present different prices and risks.

3.3.2 Single Mill Model: using Artifitial Neural Networks

The second step of the model solving process was to apply surrogates, in this case Artifitial Neural Networks (ANN), to solve the single mill optimization model described in Section 3.3.1.

As discussed earlier, the CVaR original formulation is not mathematically tractable. Its nonlinearity turns the portfolio models into a difficult to solve optimization problem. Thereby, Rockafellar and Uryasev (2000) presented an approximation approach, through the use of historical series or Monte Carlo simulation, which was used in the SUPOM's

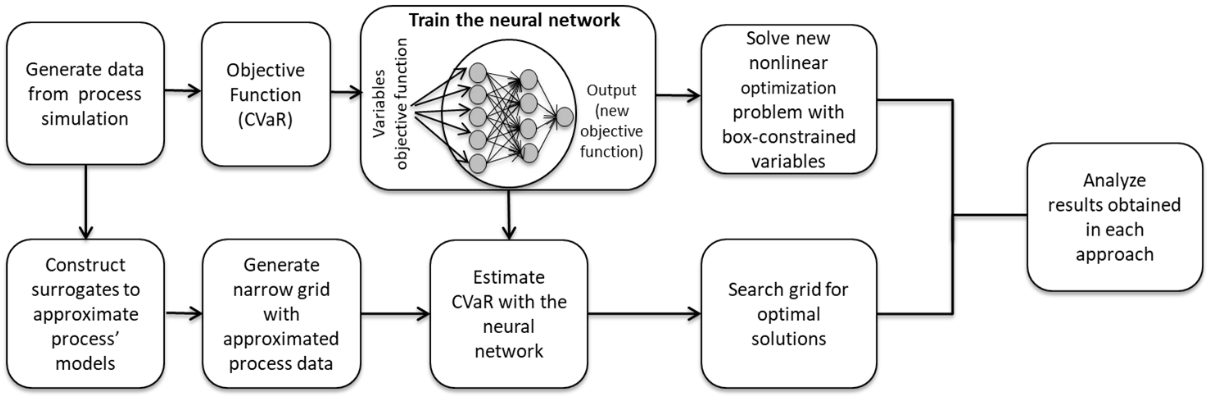

Figure 9 – Optimization framework (Source: Mutran et al, 2018)

formulation in Section 3.2.2. However, this method is extremely sensitive to the quantity of simulated scenarios (Barrosa et al, 2016) and/or to the price observations used in the sampled Profit scenarios.

In addition, the operational constraints in the model are built from the modeling of processes in the sugarcane mill. Those models (mainly the demand for bagasse in the CHP) also present some nonlinearities that shall be incorporated into the portfolio optimization problem, generating a great increase in the model's complexity.

In order to deal with this challenge, Research Article 3 proposed the use of ANNs, since they have been successfully applied in a variety of chemical engineering problems, including process modeling and optimization.

Villarrubia et al (2018) discuss the use of ANNs to approximate the objective function in optimization problems, proposing a framework for which the output function from the ANN is used as an approximation of a nonlinear objective function. Similarly, for the bioenergy investment decisions in the Brazilian sugarcane mills, the portfolio optimization model may be approximated through an ANN.

The input variables in the neural network are the amount of sugar (1) and ethanol (2) produced in each product mix, the binary investment decisions (3), and the amount of electricity commercialized to the free (4) and to the regulated market (5). The availability of surplus electricity, which may be destined to either one of the two markets, depends on the process conditions resultant from the first three input variables. The process data was simulated with the Open Sugarcane Process Simulation Platform (Castro t al, 2018) and contemplates those inherent variations in process conditions. These resultant process data were used to train and test the ANN.

The optimization framework proposed is presented in Figure 1, summarizing the two possible approaches to use ANN to approximate the solution of this complex problem. The simulated data for decision variables and the CVaR calculated for each product mix, based on the price distributions of all products in the portfolio, are used to fit the neural network, from which the approximated new objective function shall be extracted. The output function obtained from the ANN may be used to find optimal portfolios through grid search or as a new objective function for the optimization problem. In the latter application, the output function is also nonlinear, however, its complexity is reduced, allowing the use of nonlinear optimization software to solve it, while respecting the original box-constraints for the decision variables.

3.3.3 Multi Mill Model

The third step was to apply the SUPOM to a set of mills greater than 1. In the model presented in Research Article #4, $U = \{1, 2, 3\}$, and the focus of the optimization problem was to assess biogas projects in this interacting group of sugarcane mills.

The motivation for this multi mill model application was based on the findings from literature and from the interviews, that suggested that investments on Biogas projects in sugarcane mills may be incentivized by a greater availability of biomass residues. Thus, only biogas-related investment options were assessed.

The SUPOM applied in this paper considered fixed demand for bagasse and fixed surplus power available yearly for commercialization. Those two were based on the information of the sugarcane mills considered in the case study. In addition, the exchange of bagasse was considered among mills (using decision variable $w_{i,u,s}$). Finally, the Open Sugarcane Process Simulation Platform was also used to derive process conditions and yields. Figure 10 shows the graphical representation of the sugarcane mills in the interacting group, with their distances to each other and to the pipeline grid, as well as their individual installed capacities.

3.3.4 Surrogate-based Superstructure Optimization

The final step was to assess the impact of process conditions regarding the internal consumption of bagasse and electricity on product mix and investment decisions.

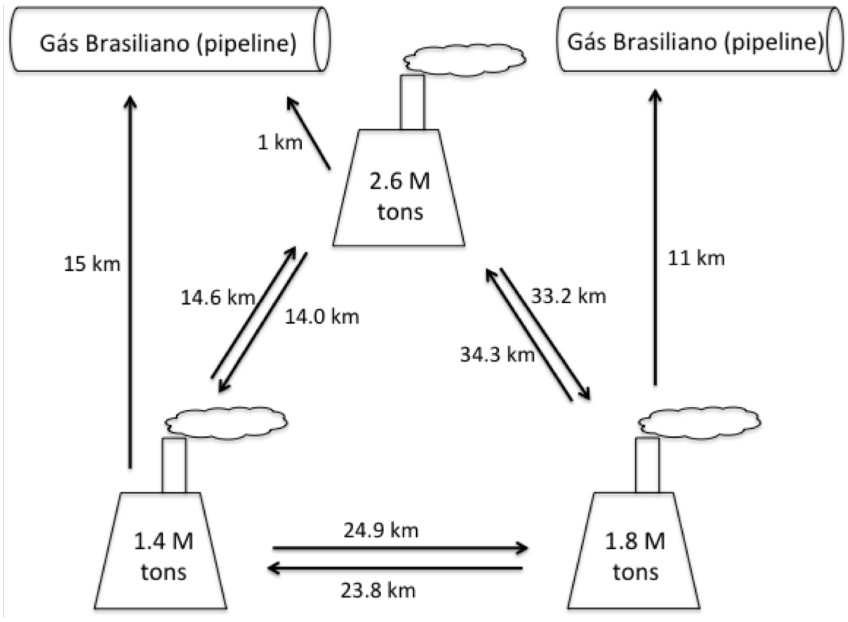

Figure 10 – Graphical representation of distances between sugarcane mills in the interacting group considered in Research Article #4.

In this final Research Article (#5), the SUPOM is applied to the case of $U = \{1\}$, but now considering the changes in surplus bagasse availability for other economic applications as a function of the sugar production.

This approach entails approximating the dependency between the yearly amount of surplus bagasse available and the sugar-ethanol production shares, with piecewise linear models that were derived from detailed plantwide simulation of the sugarcane mill of interest — using the Open Sugarcane Process Simulation Platform. Fig. 11 shows an example of simulated scenarios for surplus electrical power and 2G ethanol from bagasse.

Since part of the bagasse is used to cover internal needs in steam and electricity, only surplus bagasse is available for the production of extra saleable products. A third decision therefore entails selecting either one of the following three scenarios :

- the current scenario, which uses a traditional co-generation system and does not use all of surplus bagasse;
- investment in an improved Rankine cycle with condensation turbine, whereby all of surplus bagasse is used for extra power generation;
- investment in a hydrolysis process, which converts all of surplus bagasse to 2G ethanol.

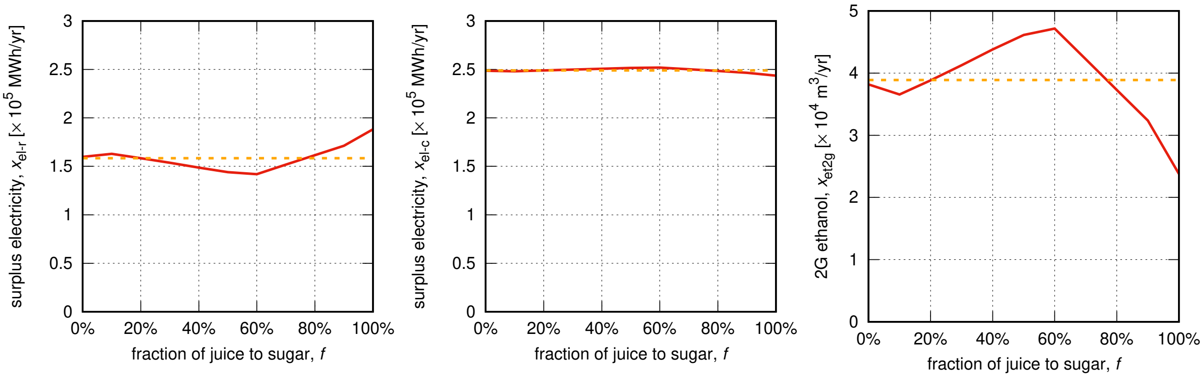

Figure 11 – Effect of the sugar-ethanol production share (f) on the production of: surplus electricity from the traditional Rankine cycle ($r_{\text{el-r,el}}$, left plot); surplus electricity from the improved Rankine cycle ($r_{\text{el-c,el}}$, middle plot); and 2G ethanol from the hydrolysis of surplus bagasse ($r_{\text{bag,eth}}$, right plot). Solid line: simulation using the Open Sugarcane Process Simulation Platform. Dashed line: average value. (Source: Mutran et al[a], 2020)

In this model, instead of applying the piecewise linear formulation to the internal demand of bagasse, we model the functions that give us the output of products in each of the above mentioned scenarios. Mutual-exclusiveness of these scenarios is enforced as:

$$1 = z_{\text{rank}} + z_{\text{cond}} + z_{\text{hydro}} \tag{38}$$

$$x_{\text{el-r}} \leq \Gamma_{\text{rank}} \left(z_{\text{rank}} + z_{\text{hydro}}\right) \tag{39}$$

$$x_{\text{el-c}} \leq \Gamma_{\text{cond}}\ z_{\text{cond}} \tag{40}$$

$$x_{\text{et2g}} \leq \Gamma_{\text{hydro}}\ z_{\text{hydro}} \tag{41}$$

A partition of the sugar-ethanol production share into L subintervals can be created via the following mixed-integer linear constraints:

$$r_{\text{jui,fact}} = \left[\hat{f}^0 + \sum_{k=1}^{L} \left(\hat{f}^k - \hat{f}^{k-1}\right) \xi_k\right] \ \text{Ca}\ \theta_{\text{cane,mill,jui}} \tag{42}$$

$$\xi_k \geq y_k \geq \xi_{k+1}\,, \quad k = 1 \ldots L-1 \tag{43}$$

where $\hat{f}^k$, $k = 0 \ldots L$ are breakpoints representing the fraction of juice sent to the sugar factory in the piecewise linear approximation; $y_k \in \{0,1\}$, $k = 1 \ldots L-1$ and $\xi_k \in [0,1]$, $k = 1 \ldots L$ are auxiliary binary and continuous variables, respectively, used to identify the correct subinterval. Then the corresponding productions of electrical power and 2G ethanol are predicted as:

$$x_i \leq \hat{x}_i^0 + \sum_{k=1}^{L} \left(\hat{x}_i^k - \hat{x}_i^{k-1}\right) \xi_k\,, \quad i \in \{\text{el-r}, \text{el-c}, \text{et2g}\} \tag{44}$$

where $\hat{x}_i^k$, $k = 0 \dots L$ denote the predicted yearly production of product i for each juice fraction breakpoint $\hat{f}^k$.

Notice that an inequality is used in Eq. 44 as the actual production of i may only be nonzero when the corresponding technology is selected (Eqs. 39–41); instead we rely on the optimizer (Sec. 3.2.2) for maximizing the production.

3.4 Implementation

To test and validate each step of the model development, case studies with real data from sugarcane mills in the state of São Paulo were conducted.

Price variations for all saleable products were obtained from weekly price records for the period of 2002 and 2018 — —a total of $Q = 868$ observations, all expressed for the same base year (2010 USD), discounting the effect of inflation (See Figure 5). Production, transportation and investment costs were obtained from the literature.

The process yields, waste generation rates and internal consumption of steam and power are derived from the Open Sugarcane Process Simulation Platform (Castro et al, 2018). The operation conditions and process specifications used for the simulation of the generic sugarcane plant are presented in Table 5.

Parameter	**Value**
Fibre % Cane	13.0%
Sucrose wt%	15.0%
Bagasse	26.6%
Extraction efficiency	97.7%
Boiler steam pressure	67 bar
Boiler temperature	520°C
Boiler efficiency	79%
Back pressure turbine efficiency	82%
Condensation turbine efficiency	73%

Table 5 – Operation Conditions for Simulation

3.4.1 Case Studies: single mill

For the single mill cases (steps 1, 2 and 4), the case studies were applied to a sugarcane plant that processes 3 million tonnes of sugarcane per year, an average-size plant in Brazil. Sugar and ethanol are produced in an integrated production system, and it was assumed that the shares of juice can range between 0% and 100% for both products. That is, the industrial mix is assumed to be completely flexible, allowing the producer's production decisions to be based solely on the market conditions.

The initial configuration of the cogeneration system is a traditional Rankine cycle running with a 67 bar boiler at 520°C and generating an average surplus electricity of 53 kWh per tonne of sugarcane processed. As investment alternatives to increase energy generation from biomass residues, were considered:

- The addition of a condensation turbine of 40 MW that increases surplus power generation to an average of 83 kWh per tonne of sugarcane (steps 1, 2 and 4);
- The introduction of a hydrolysis process for the production of 2G ethanol using the surplus bagasse (step 4);
- The installation of a digestor for vinasse alongside a system of reciprocating combustion engines (RCE) for power generation with the resultant biogas (step 4).

3.4.2 Case Studies: multi-mills

The São Paulo Energy and Mining Secretary mapped 66 sugarcane mills located under 20 km of the existing pipeline infrastructure, for which investments in biogas draining may be economically feasible (see Fig. 12). In this case study, the model was applied to 3 out of these 66 sugarcane-processing plants (U = {1,2,3}) that belong to the same economic group and for which the distance from one another is within 35 km. They are located respectively 1 km, 11 km and 15 km from gas distribution infrastructure in the city of Araraquara. Their annual milling capacities (Ca_u) are 2.6, 1.8 and 1.4 million tons of sugarcane, with production of sugar and ethanol in the first two and only sugar in the last one.

Bagasse is the only resource allowed to be exchanged among mills, and its transportation is done in trucks with a maximum capacity of 25 tons per trip, which results in a cost per tonne of bagasse transported of US$ 0.18 / km. The round-trip distances between mills are 67.5 km between mills A and B, 28.6 km between A and C, and 47.7 km between B and C. All remaining resources were used internally in each mill in accordance with production decisions in the model.

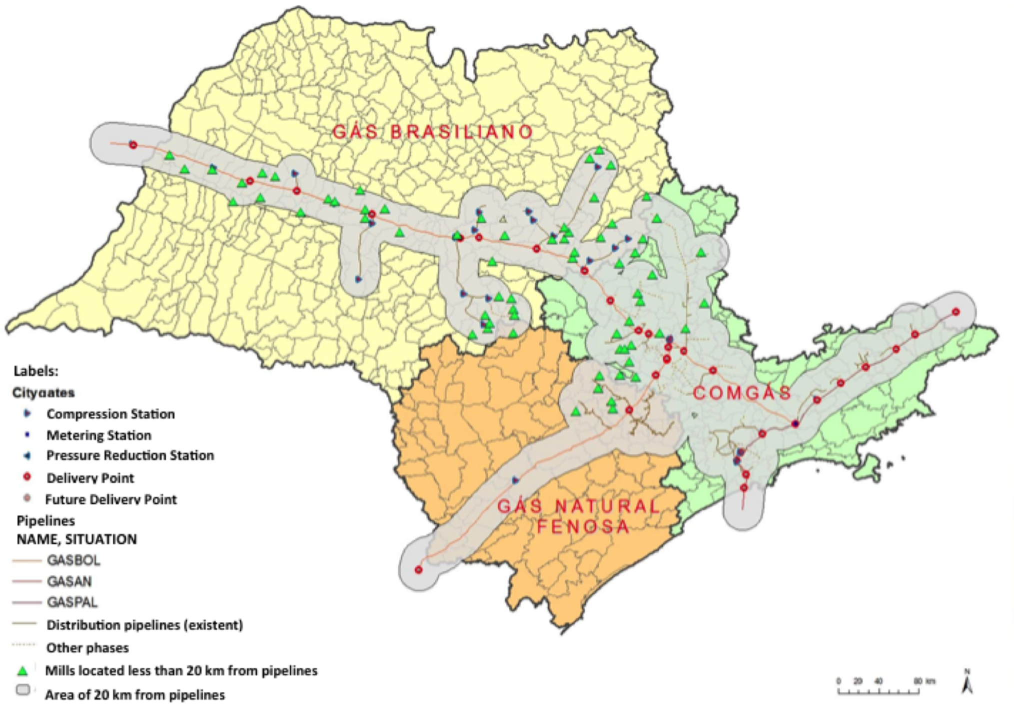

Figure 12 – Map of 66 sugarcane mills located within 20 km from the pipeline infrastructure in the State of São Paulo (Source: ARSESP, 2017)

The first-generation processes (for sugar and ethanol), along with the cogeneration system installed were already existent in each mill. Thus, investment costs were only applied to biogas-related process units (or equipment). All the interacting mills considered in this example already generate bioelectricity to the national grid, with installed capacity of 16 MW, 16.2 MW and 6.6 MW respectively. In order to increase this capacity, the investment options considered is to install an energy generation system using biogas produced either from bagasse or vinasse. This is still an incipient technology, and the related investment costs were based on literature (Pazuch et al, 2017).

Another possible destination of the biogas is to be sold as a competitor to natural gas, implying a need for investments on a technology to upgrade biogas to the appropriate methane specification (Leme & Seabra, 2017), and on pipeline infrastructure to its draining to the regional gas distribution (EPE, 2014).

A third and final investment option considered in this study is on the conversion of diesel trucks into gas-fuelled engines. They are currently used for the transportation of sugarcane from cultivation areas and represent around 30% of the total production cost. Thus, the income for this investment option is given by the savings resultant for the displacement of costs with diesel, given the respective energy equivalences between the two fuels (Moraes et al, 2014).

4 Results and Discussion

4.1 Paper #1: Qualitative Research

The first phase in the development of the proposed decision-making system was to identify the main factors involved in product mix and investment decisions in the sugarcane sector. Thereby, Research Article #1 presents a qualitative analysis of past dynamics and future drivers for the Brazilian sugarcane industry, based both on historical data and on semi-structured interviews with experts in the sugarcane and energy sectors in Brazil.

The goal of this paper is to understand the main drivers affecting demand for sugar, ethanol, biogas and bioelectricity in the short, mid, and long-terms. The results obtained gave insights on the role governmental policies may play in the future of the sector, what technological routes are more likely to stand out in the coming years and what are possible market scenarios for the main products in the sugarcane industry. This paper also allowed the identification of the main variables for the development of a reliable decision-making system to assess investments in new bioenergy generation.

Fig. 13 summarises the interviewees' responses when asked to project their expectations for the whole sugarcane sector, and the four principal products, in the short, medium and long term. The figure illustrates that expectations of increased future activity were widely held across the interviewees. This expectation was particularly strong in relation to the three energy products, ethanol, electricity and biogas, for which, across all three time horizons, interviewees expecting increased activity accounted for 72% (13) to 100% (18) of responses. No interviewee expected decreased activity for the three energy products in any of the time horizons – although three expected no activity at all for biogas in the short term, indicating the incipient stage of this technology.

4.1.1 Perspectives on the future of the four main products

Traditionally, sugar has been the main product of the sugarcane industry worldwide. But the diversification to other products, in particular with the incentives for ethanol production, were paramount to position Brazil as the main sugarcane producer in the world.

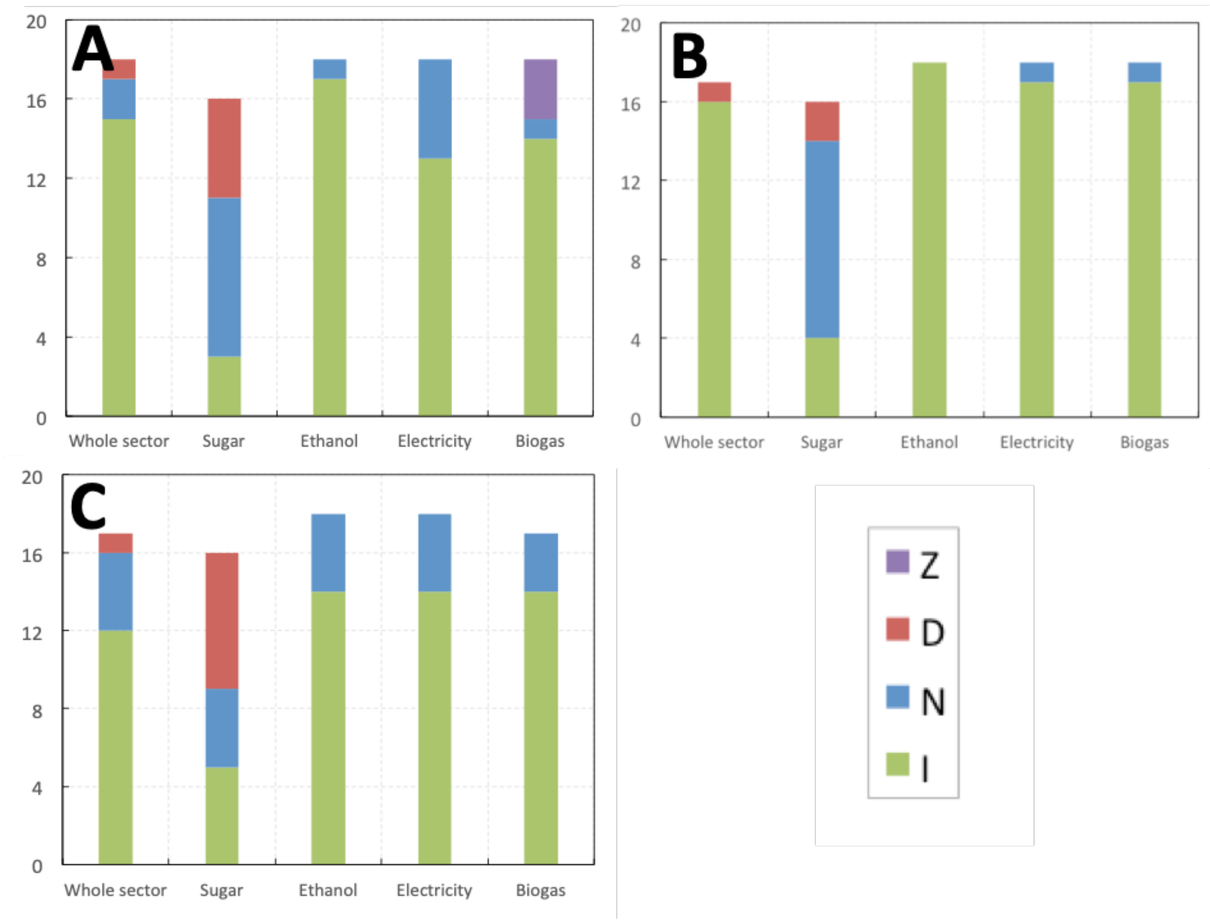

Figure 13 – Interviewees' projections for the whole sugarcane sector, and for its main products, in the short-term (**A**), mid-term (**B**), and long-term (**C**). **I** = Increase; **N** = No Change; **D** = Decrease; **Z** = No activity at all. (Source: Hughes et al, 2020).

Although sugar still plays an important role in this industry's business, interviewees had mixed opinions on whether this product would still thrive for many years, and most of them predicted an stabilisation, or even a decrease in sugar consumption in the long-term. Therefore, this expectation increases the call for diversification towards energy products.

In this context, the high sensitivity of the ethanol business with regards of governmental policies in the energy sector was broadly discussed by the stakeholders interviewed. While positive policies (such as PROALCOOL and flex fuel vehicles) were highlighted as important drivers for the increase in ethanol production in the sector, controversial policies from the past decade were also identified as the causes for an important crisis that is still undergoing.

Despite the current adverse scenario, stakeholders in general showed optimism for the future of the sugar-energy sector. This was mainly because of the RenovaBio program, which is expected to significantly increase the demand for ethanol in Brazil in the coming decade.

In terms of the future of ethanol production, Second Generation ethanol elicited mixed opinions from interviewees. One described the technology as "ready", but the majority of the stakeholders were more cautious, based on the experiences of the past decade. Essentially, ethanol 2G is seen as a product that could completely change the ethanol sector, but it's still not feasible. The general sense is that we still have to "wait and see".

RenovaBio is also seen as a promising program to incentivize (even if indirectly) new bioelectricity projects, *"as power plants that export electricity have a better carbon footprint and can earn more CBIOs"* (IND5). Interviewees highlighted that there are still many challenges in increasing bioelectricity generation in sugarcane mills, emphasizing the lack of scale and unfavorable market conditions (mainly due to low prices) among the reasons why this is not a very attractive business to some producers.

Finally, biogas projects were also pointed as potential beneficiaries of RenovaBio. Despite the still existent technological challenges to biogas generation from vinasse and bagasse, in general interviewees believed this product would be in the mix of sugarcane mills in the mid-to-long terms. The main economic applications identified were to be sold in pipelines to compete with piped natural gas, to be applied in power generation, and to be used as fuel for trucks in the sugarcane plantation areas, with the displacement of diesel. However, the lack of extensive existing infrastructure caused some to argue that biogas could have advantages as a small-scale distributed option, used for internal industrial processes, even though some economies of scale would be most likely required to make the product cost competitive.

4.1.2 Other relevant topics discussed

In addition to their perspectives on the four main products in the industry, the interviewees also discussed about other topics regarding the future of the sector. The cross-cutting themes that were more relevant to support the modeling are summarized below. For a thorough presentation of the experts' perspectives, see Appendix A.

Sugar and Energy Markets: Sugar is a commodity worldly traded. Even though Brazil plays a major role in this business, it is still affected by crop scenarios of other countries, demand worldwide and the introduction of new players, and there is a relevant price variation for this product. Ethanol, in turn, is mainly sold in the domestic market, and is highly affected by governmental policies — especially those related to gasoline prices. In the beginning of the 2000s, the government was committed to increase biofuels in Brazil and there was a boom of ethanol production incentivized by the introduction of flex fuel vehicles. This also promoted a significant increase in bioelectricity generation, as the expansion of sugarcane mills coincided with a good scenario for long-term contracts in the regulated market of commercialization. However, today this power source is struggling to compete with other renewables, such as wind and solar. Finally, since biogas is a nascent product, there's still a need to create a market for it. Probably, biogas will be used for internal consumption or as an alternative product to natural gas. However, all possible applications demand a significant investment in infrastructure, since the Brazil does not have a very strong market for gas as a fuel.

Energy Policies: The production and investments decisions regarding all energy products in the sugarcane industry are very sensitive to policies in place in the energy market. Some stakeholders from the industry mentioned that there's still a call for a more clear mid-to-long term policy for the sector, so they can have more confidence in committing to new investments. On the other hand, there was a mix of opinions regarding the level of interference that the government should play, and most of the interviewees were excited with the introduction of a new program to incentivize biofuels through pricing energetic and environmental efficiency in their production – RenovaBio. The general sense with the expectation of RenovaBio is of optimism towards ethanol production, but there is still a lot of uncertainty regarding the path that will be followed in the long-term future, with all the technologies available (i.e. ethanol 2G, biogas, electrical vehicles, fuel cell vehicles, etc). As for the other energy products, bioelectricity and biogas, even though they can indirectly benefit from RenovaBio, the current scenario still shows a lack of public policies to incentivize new capacity insertion, specially for smaller/family producers, who don't have much access to capital.

Industry structure: In the State of São Paulo, sugarcane is the main agricultural activity in all municipalities in which there are appropriate climate conditions for its plantation, and consequently the state holds a large number of sugarcane mills — 172 out of the national total of 410 mills (Nova Cana, 2019). A particularity of the sugarcane business that contributes to this high number of processing plants is that there's a maximum distance between the plantation areas and the mill to maintain the economic viability for the logistics of the cane: around 25 kilometers, according to some interviewees from the industry. Thus, even though we have seen a relevant consolidation of the sector in the early 2000s — specially with the entry of large foreign companies — most processing plants were maintained in their original locations, making it common for one large company and/or economic group to own a cluster of sugarcane mills within a single area. Furthermore, there are still many smaller family firms spread across the country, making the sector a very heterogeneous industry, specially in terms of technological development and energetic efficiency. Several interviewees commented that the size and access to capital of larger actors means they have better potential to invest in more diverse and technologically advanced options (such as biogas, bioelectricity or second generation ethanol) than the smaller family companies. But one interviewee from the industry went on to say that he did not believed some technologies would be adopted by all mills. Instead, he thought it more likely for us to see a scenario of 1 out of 4 or 5 mills located in a certain area making investments in high-cost technologies, such as biogas or ethanol 2G — which demand a large amount of biomass to become economically feasible.

4.1.3 Main takeaways from the qualitative research to the model

During this first part of the research, it was possible to have a better understanding about the dynamics of the sector and to obtain a few takeaways to be used in the modeling process.

First of all, it is clear that sugar and ethanol still remain the primary business of sugarcane mills, and that flexibility in the production between those two products plays a major role in reducing financial risks. As a commodity, sugar has seen a historical volatility in prices, while the market for ethanol has been both positively and negatively affected by governmental policies in the energy sector. That is, the sector has shown quite a relevant lack of stability over the past 50 years, and the mills' capacity of shifting from one product to the other given different market scenarios is paramount to their economic survival. Thus, the model has to take this major production decision into account and assess the product mixes under the perspective of price risks.

Second, three main technological routes were identified for the near future of the sugarcane business: improved bioelectricity generation, biogas generation, and ethanol 2G. All three options still present many challenges, specially as the market scenarios haven't been very promising for the output products of these technologies, but it is important to assess how public policies (such as RenovaBio) may influence positively the sugarcane sector to become more energetically efficient.

Thirdly, the structure of the industry, as discussed in the previous section, may promote an exchange of byproducts among mills that are located in the same area, since some technological routes can benefit from a larger amount of biomass availability to become economically feasible. Hence, this condition shall be considered in the model.

Lastly, from the literature review, it was possible to identify a theoretical gap in the modeling of production and investment decisions in sugarcane mills, since previous studies addressing risks in the sugarcane industry haven't considered the process interdependencies of sugar-ethanol product mix decisions with the availability of biomass and energy for other energy-related processes.

Given these takeaways about the sector, the decision-making optimization framework proposed by this Thesis was developed. The results obtained in each step of the modeling process will be presented and discussed in the following sections.

4.2 Paper #2: Single Mill Sugarcane Portfolio Optimization Model

The efficient frontiers for all four price scenarios are shown on the left plot in Fig. 14. The model predicted two distinct behaviors within the range of regulated electricity prices investigated in the sensitivity analysis (US$50-100 per MWh): one when the price in the regulated market is lower than or equal to the expected price of the free market, and the other one when it is higher. This is expected since the regulated prices are not subject to variations and are essentially risk-free. Consequently, when regulated prices are greater than the expected value of prices in the free market, a decision-maker will always choose

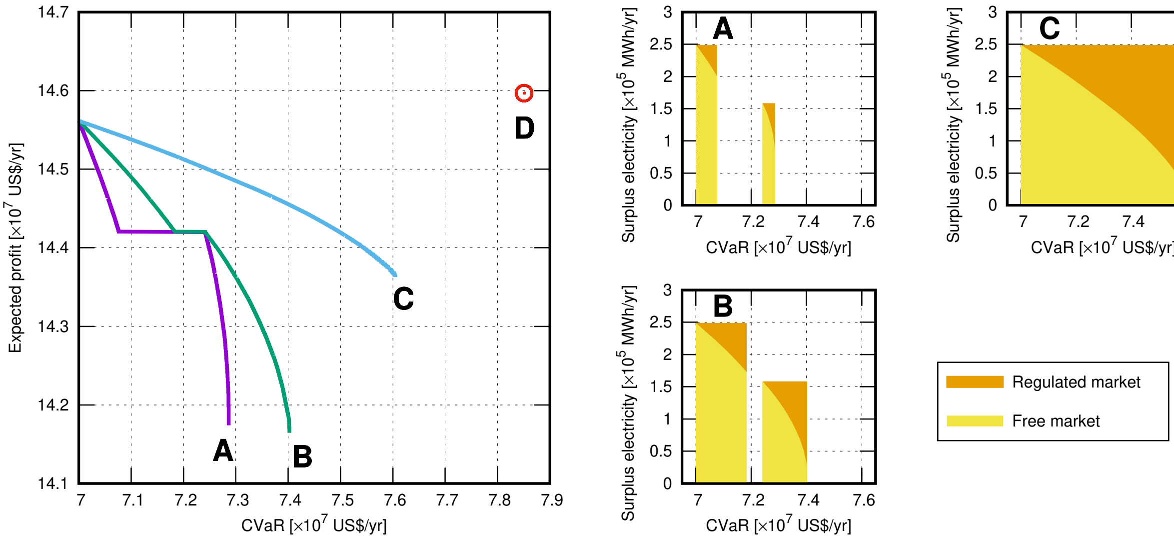

Figure 14 – Efficient frontiers and annual surplus electricity sales in the free and regulated markets for different regulated price scenarios. **A**: US$50/MWh; **B**: US$60/MWh; **C**: US$70/MWh; **D**: US$80/MWh. (Source: Mutran et al, 2019)

to sell to the regulated market. Given the expected free market price of US$78 per MWh, this latter behavior is clearly seen in Fig. 14 (scenario **D**).

The three frontiers for which regulated market prices are lower than the expected price in the free market (scenarios **A**–**C**) all originate from the same point, where a risk-inclined producer would invest in a condensation turbine to improve power generation, and would sell all of its surplus electricity to the free market.

For regulated price scenarios in the range of US$50-60 per MWh, the Pareto frontier presents a significant jump because the decision to invest is not made until the risk level is quite high. The sales decisions only change among prices in this range when risk starts playing a more important role than expected profit in the investor's decisions.

Regulated prices of US$70 per MWh or higher are sufficiently attractive to promote the investment, and we no longer observe a jump in the Pareto frontier. There is also a clear tendency for risk-averse profiles to prefer the regulated market in all of the regulated price scenarios.

There is also a notable gain in efficiency as the prices in the regulated market increase. Clearly, raising the regulated market price reduces the gap between the expected profits in risk-averse and risk-inclined strategies, evidencing how long-term electricity contracts may play a relevant role as a strategy to mitigate risks.

Finally, the results obtained with the cost conditions of the case study suggest that a price range between US$65-70 per MWh in the regulated market would raise the interest of risk-averse investors in implementing a condensation turbine to increase their surplus electricity generation.

4.3 Paper #3: Combining Neural Networks and Portfolio Theory

Instead of a long series of historical price observations (as in Research Article #2), in this paper a much shorter price series of only 100 points is used to create a neural network that approximates the distribution of prices for sugar, ethanol and free market electricity.

The price data and simulated process data were used to train neural networks with the Software R. The neural network that presented the best fit with the training set had one hidden layer with four neurons. Two approaches were used to solve the optimization problem with the ANNs. The first one was to use the output function of the trained neural network as a new objective function for the optimization. The Augmented Lagrangian Method was chosen among the nonlinear optimization packages in R to solve this problem, subject to box-constraints for decision variables, aiming to maintain feasibility of process conditions in the final solution. The optimization problem was solved also for a variety of levels of profits, in order to build the efficient frontier of the trade-off risk and profit.

The use of the ANN as a new objective function for the optimization problem presented some disadvantages, as the algorithm showed a relevant sensitivity to the starting points for search, in some cases resulting in the inability to find solutions within the constrained space. In regards of the results obtained, the portfolios built presented a tendency of increasing sugar production as expected values of profits were incremented, and it also showed a preference for the regulated market. This latter appears to be a manner to reduce risks, as this asset is risk-free, but most of these results failed to maintain process feasibility, which indicate that the use of the output function of ANN to solve for CVaR is not an appropriate approach.

The second approach was to apply ANNs in the traditional manner, and create a narrow grid with process and market conditions, to search within it for optimal solutions. For the portfolio results, quantities of sugar were also increased as expected profit grows.

However, instead of leading production to unfeasible levels, the portfolios showed an increment in the electricity commercialized to the free market, which increases profits while raises the overall risks. Furthermore, results evidenced that the investment option in the condensation turbine causes a gain in efficiency in the frontier of risk-profit.

Even though a shorter price series was used, the results obtained with the ANNs corroborate with the findings of the Research Paper #2, since the model also presents a tendency to commercialize electricity in the free market when seeking for higher expected profits, as well as a preference for producing sugar.

Lastly, although the use of ANNs gave interesting insights of the sugarcane portfolio optimization, the method proposed by Rockafellar and Uryasev (2000) with the use of historical price data was considered a more appropriate approach for the next steps.

4.4 Paper #4: Multi-Mill Sugarcane Portfolio Optimization Model

Research Article #4 introduces the sugarcane portfolio optimization model applied to a group of interacting sugarcane mills. In this new version of the model, biomass resources (in this case, the bagasse) may be exchanged among processing plants in order to maximize the profits provided by investments on new biogas technologies. This adds a logistic component, as the transportation costs of sending resources from one plant to the other have to be considered, but the model is still classified as an MILP of low complexity since fixed process configurations (both for existing processes and new investments) were assumed, as well as deterministic process conversion rates. Interestingly, the results obtained indicate that the choice of investing in a particular biogas technological route depends mainly on the processing plant location and size, rather than on the prices or risk-profile of investors.

Given that regulated market prices are assumed to be risk-free, an increase on these prices promotes a gain in efficiency in the trade-off risk-profit (see Fig. 15–left). Naturally, this is reflected on the surplus electricity annual sales (see Fig. 15-right), which show a consequent increase in the shares of electricity sold to the regulated market as risk-aversion grows.

These results corroborate with results of Research Articles #2 and #3, that assessed the impact of regulated prices on bioenergy investment decisions. However, an interesting

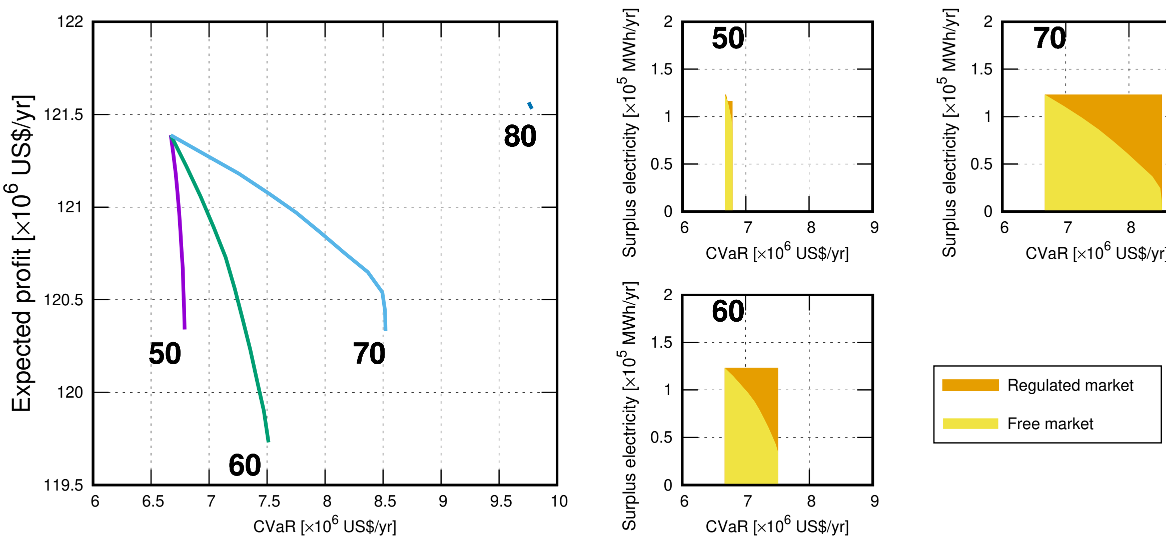

Figure 15 – Efficient frontiers (right-plot) and surplus electricity sales in the free and regulated markets (left-plot) for price scenarios of US$ 50/MWh, US$ 60/MWh, US$ 70/MWh and US$ 80/MWh. (Source: Mutran et al,2020[b])

finding of the Research Article #4 is that investments on biogas projects are less sensitive to governmental policies in the power sector and to price risks. In all scenarios of prices and risk-aversion assessed, the model consistently chose to invest on biogas generation from vinasse, which evidences the economic feasibility of this technological route.

The choices for investment related to the application of biogas were also consistent throughout the scenarios. In all three mills, the model chose to invest in the conversion of 100 trucks to be biogas-fuelled. For mill A, which is the closest to the pipeline infrastructure, the model chose to invest in two biodigestors for vinasse and one for bagasse, and in the purifier system with associated pipeline to drain biomethane to the grid. For mill C, which produces only sugar, the investment on biogas generation from bagasse was also consistently indicated, using imported bagasse from mill B. Mill B, on the other hand, diverted in investment decisions between the risk-neutral and the risk-averse scenarios, for the regulated price of US$ 50/MWh. In this mill, the choice of investment in a gas turbine for electricity generation was consistent in all scenarios, but for such low price of electricity, the amount of power generated was reduced, since the model did not invest on the biodigestor for bagasse, producing only biogas from vinasse. Table 6 summarizes all investment decisions in this price scenario.

Finally, Figure 16 depicts the applications of biogas and bagasse for different regulated price levels, which evidence that rather than being sensitive to the price policies

Table 6 – Investment decisions for Regulated Price of US$ 50 / MWh

Risk Profile	**Biogas (bagasse)**	**Biogas (vinasse)**	**Gas Turbine**	**Piped Methane**	**Trucks (100)**
Risk-Averse	A,C	A(2), B	B	A	A,B,C
Risk-Neutral	A,B,C	A(2), B	B	A	A,B,C

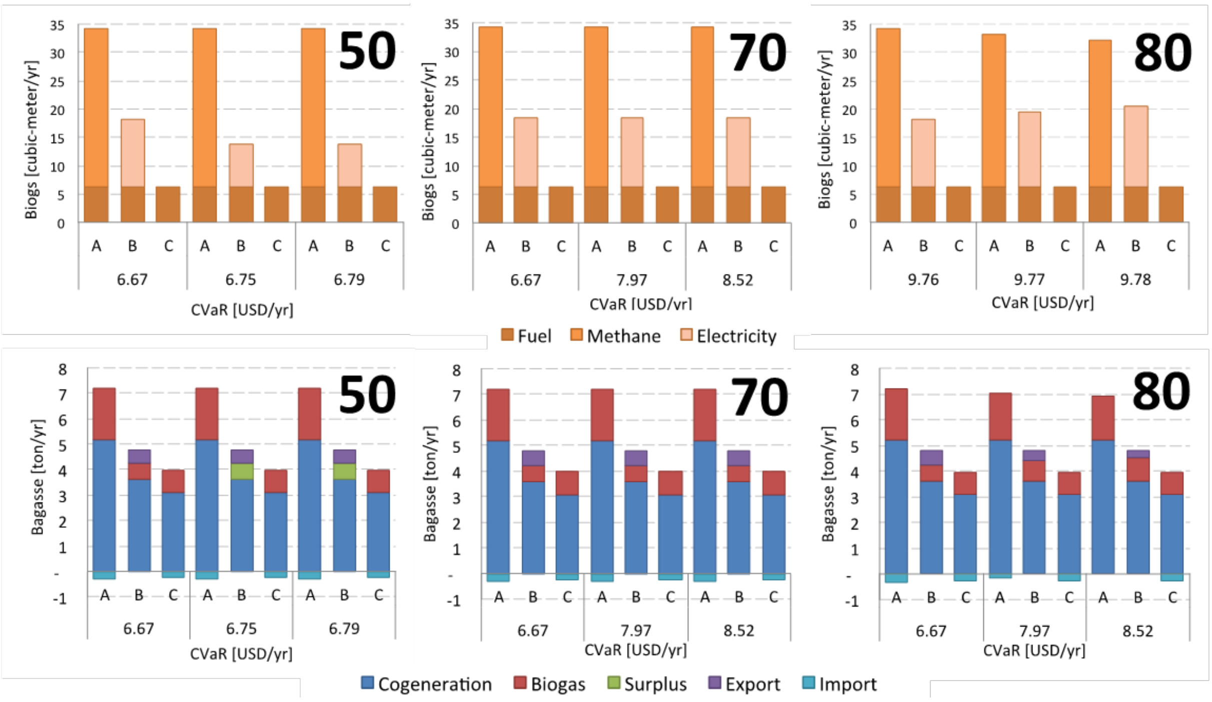

Figure 16 – Production decisions for the use of biogas (top plots) and bagasse (bottom plots) at regulated market price scenarios of US$ 50 / MWh , US$ 70 / MWh and US$ 80 MWh. (Source: Mutran et al,2020[b])

or risk levels, the investments are more impacted by the location of mills and their sizes. This is shown by the great diversity of production and investment decisions among mills. For instance, it is clear that the biggest amount of biogas is generated in mill A, and sold as piped biomethane – which in turn is promoted by the large amount of biomass available in this mill, and its coincidental location close to the pipeline. Mill B, located further away from the gas infrastructure, exports surplus biomass to the two other processing plants and chooses instead the investment on power generation – a less capital-intensive option. Lastly, the investment in the conversion of trucks for biogas is shown to be an interesting alternative to all mills, regardless of their size, process configurations and location.

4.5 Paper #5: Surrogate-based Superstructure Optimization

Finally, Research Article #5 presents the Sugarcane Portfolio Optimization Model combined with surrogate modelling of process conditions. The goal of this paper is to increase the reliability of the decision-making system by taking into account the variation in steam and power consumption caused by changes in the production mix for sugar and ethanol.

Since in this version of the model the internal consumption for thermal and electrical energy are expressed as functions (rather than parameters), there is an increase in the complexity of the optimization problem. Nonetheless, the piecewise linear formulation approach was used to approximate the output function of process simulations that accounted for different scenarios of product mix and process configurations. Thus, the final model still falls into the class of Mixed Integer Linear Programming (MILP).

The application of this model allowed a comparison with the results obtained in the model using fixed parameters, to assess the sensitivity of investment and production decisions to the changes in the process's energy consumption (namely the demand for bagasse).

This paper also presented an extensive sensitivity analysis and provided key insights to which technological routes are more likely to be implemented to increase bioenergy generation in sugarcane mills, as well as to what policies should be created to incentivize those new bioenergy projects. The main results obtained will be detailed in the following subsections.

4.5.1 Effect of modeling assumptions

Assuming a regulated electricity price of US$ 72.50/MWh, the first analysis performed was the comparison between solutions of the SUPOM with either piecewise-linear (**base**) or constant (**fixed rate**) profiles of surplus electricity and 2G ethanol (see Fig. 17).

There is a notable difference between profiles computed with the piecewise-linear and constant approximations on the main plot of Fig. 17, showing a reduction of more than US$1MM/yr in expected profit of the model with fixed-rates. Another key difference between both models is in terms of investment strategy: the portfolio model with the constant approximation (**fixed rate**) recommends investing in an improved Rankine cycle

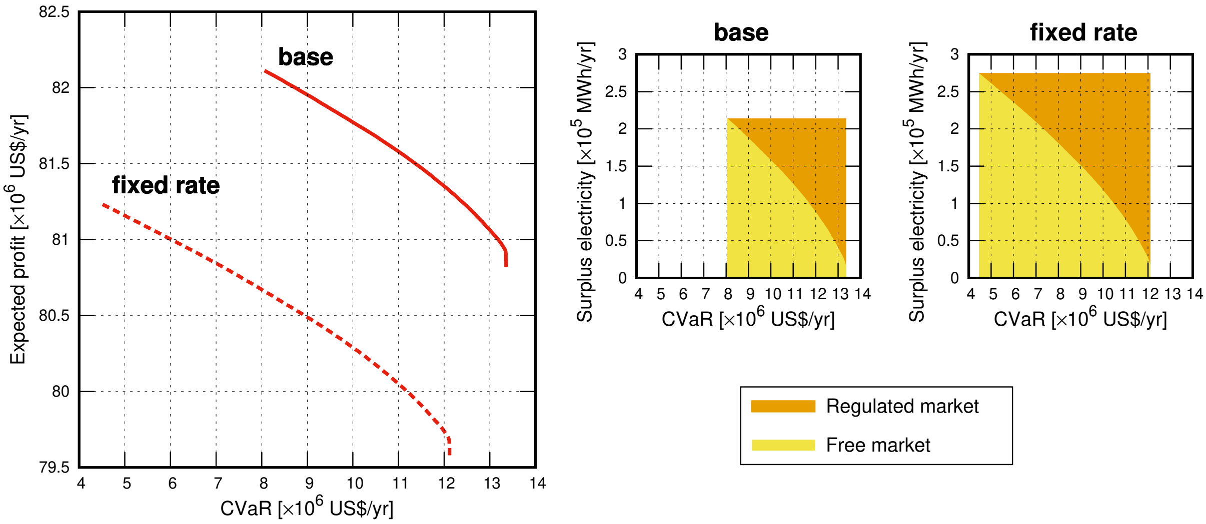

Figure 17 – Comparison between optimal portfolio solutions with either piecewise-linear (**base**) or constant (**fixed rate**) profiles of surplus electricity. Main plot (left): Pareto frontier of expected profit versus risk. Secondary plots (right): share of surplus electricity between free and regulated markets under each modeling assumption (Source: Mutran et al, 2020[a]).

with condensation turbine; whereas the piecewise-linear model (**base**) advises against this investment (see the two secondary plots on Fig. 17). On the other hand, the two models present a similar strategy for the sale of surplus electricity between the free and regulated markets, favoring the regulated market for risk mitigation.

In both models, all of the sugarcane juice is directed to the sugar factory, and ethanol is produced only from molasses. Thus, the surplus electricity from the traditional Rankine cycle is indeed underestimated by some 20% with the constant approximation, while at the same time the surplus electricity from the improved Rankine cycle is slightly overestimated (see Fig. 11). In fact, this comparison is a clear illustration of how sensitive the decision-making can be to the process models. The piece-wise linear approach is used in the remaining of this work, which enables a better description of the interdependencies between decisions and variables in the sugarcane plant.

4.5.2 Sensitivity of investment decisions

We observed in the past subsection that with the piecewise-linear model of surplus bagasse, the addition of a condensation turbine to the existing co-generation is not chosen, regardless of the risk level (CVaR). In fact, when we consider the process models for

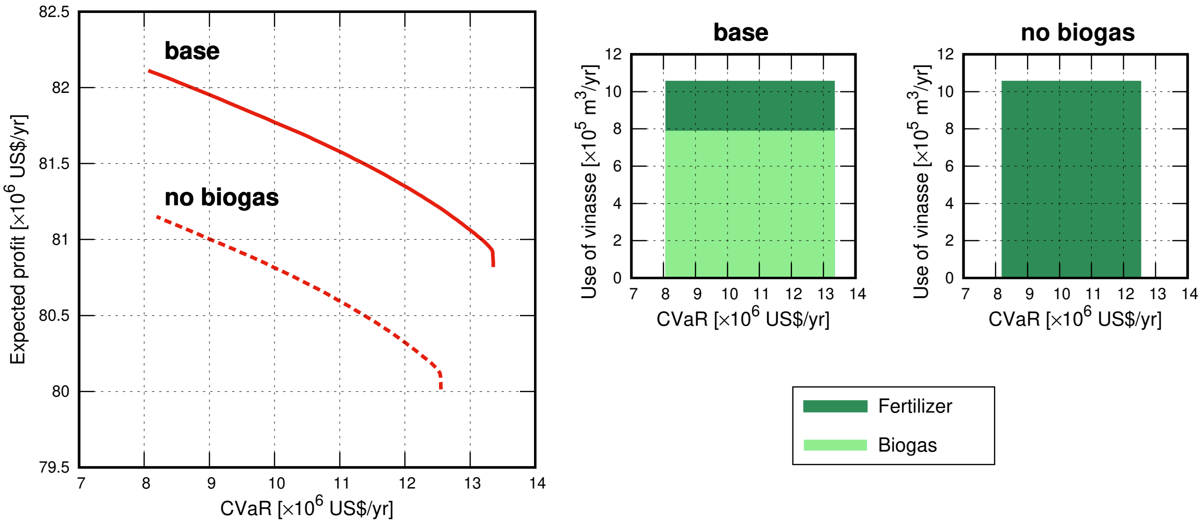

Figure 18 – Comparison between optimal portfolio solutions with (**base**) or without (**no biogas**) investment on biogas generation from vinasse. Main plot (left): Pareto frontier of expected profit versus risk. Secondary plots (right): share of vinasse between fertilization and digestion under each scenario (Source: Mutran et al, 2020[a]).

surplus electricity, this investment would only be advisable with a reduction of about 30% in investment costs. Note that this differs from results obtained in the previous models (Research Articles #2 and #3), but corroborates with insights obtained in the interviews — in which stakeholders complain about the lack of competitiveness of bioelectricity sources in the current scenarios of the Brazilian energy market.

On the other hand, the SUPOM advises to invest in extra electricity generation via the anaerobic digestion of vinasse. A comparison between the solutions of the portfolio optimization model eq:portfolio2 with (**base**) and without (**no biogas**) such an investment is presented in Fig. 18. Electricity generation through biogas combustion leads to a noticeable gain in expected profit, around US$1MM/yr. The financial shortfall corresponding to the risk-averse solutions is furthermore reduced by close to US$1MM/yr. Though still incipient in the sugarcane sector investment in new biogas capacity is predicted to have a very short payback period in our base scenario, which corroborates with other studies in the literature (Salomon et al, 2011; Pazuch et al, 2017) and with findings of Research Article #4.

Another key insight from our base scenario is that the investment in a hydrolysis process to produce 2G ethanol from surplus bagasse may not be economically viable by a very large margin. For comparison, the maximal expected profit in a risk-neutral setting is predicted to decrease to below US$40MM/yr in case this investment was made, a 50% downfall with respect to the best portfolio solutions. The contributing factors are two-fold: the investment cost of the hydrolysis process is high relative to a traditional or improved co-generation system; and due to an unfavorable ethanol market, selling ethanol could lead to large financial losses in the worst-case scenarios (negative CVaR). The unfavorable ethanol market was already reflected in the fact that 100% of the sugarcane juice is sent to the sugar factory, while only producing 1G ethanol from molasses. Once again, this result supports the recurrent concern of stakeholders in the interviews regarding the feasibility of ethanol 2G given current scenario of technological development and investment costs.

4.5.3 Effect of sugar-ethanol capacity constraints

As discussed by stakeholders in the interviews, the greatest advantage of the Brazilian sugarcane industry in comparison with other producing countries is the flexibility in production between sugar and ethanol. Not only does this increase the economic efficiency of the sugarcane production, but also allows for price risks mitigation.

Based on the historical prices used for the solution of this optimization model, there is a clear preference for a product mix focused on sugar production. In the base scenario, which assumed a fully flexible configuration of the mill, 100% of the sugarcane juice was destined to sugar production, while ethanol was only produce with molasses.

Accordingly, as we reduce sugar production capacity (that is, decrease the level of flexibility), there is also a loss in efficiency in the portfolio optimization model. These results are most likely due to unfavorable ethanol prices practiced in the Brazilian market in the past 10 years, mainly due to governmental policies that were focused on the oil market.

An interesting insight drawn from the model, however, is that the piecewise linear model starts to advise for the investment on the condensation turbine when sugar production capacity is below 85%. This demonstrates that product diversification with bioelectricity may be an interesting strategy to reduce the risks with the ethanol price variations.

In the following subsection, some scenario analyses will be performed to assist policymaking to efficiently attract more energy generation in the sugarcane sector.

4.5.4 Effect of market and governmental policies

According to the results obtained in Secs. 4.5.1 and 4.5.3, the portfolio optimization based on historical prices clearly supports a production focused on the sugar business. These results also corroborate with those obtained in Research Papers #2, 3 and 4. However, this strategy goes against the understanding of the sector's main stakeholders, who mostly see a future focused on bioenergy products.

To analyse the potential impact of price policies on the production of ethanol, specially as we see great expectations for RenovaBio, let us first assess how an increase in prices could change the product mix decisions.

A scenario with capacity constraint of 70% on the amount of juice processed by the sugar factory is assumed, (an average for Brazilian sugarcane mills), and the electricity price in the regulated market is set at US$72.50/MWh as in the base scenario (Sec. 4.5.1).

When this capacity constraint is set, the risk-taking scenarios lead to negative values of CVaR (that is, to potential shortfalls in case of detrimental price scenarios). Interestingly, a rise in only 6% rise in ethanol prices (**HP+6%**) is sufficient to mitigate the risk of financial losses even in a risk-neutral strategy. The corresponding increase by about 8% in the expected profit demonstrates how dependent and sensitive the profitability of a sugarcane mill can be to the ethanol business. However, this mere 6% rise in market price of is not sufficient to incentivize 1G ethanol production, as the plant still operates at maximum sugar production capacity in this scenario (that is, destining 70% of juice to sugar).

For the production of 1G ethanol to become preferable over sugar a 30% increase in the historical prices of ethanol would be necessary. This seems highly unlikely in the near future, insofar as ethanol needs to remain (at least) 30% cheaper than gasoline for economic competitiveness in Brazil (Castro et al, 2019).

Although this scenario of ethanol seems still challenging, we can rely on another relevant characteristic of RenovaBio – the potential of increasing profitability with gain in efficiency with respect to environmental aspects. As pointed out by some stakeholders in the interviews, despite the current disadvantages of bioelectricity in the power sector, it can be indirectly incentivized by the biofuel program.

Once again, the role of prices in the regulated market is analysed, similarly to results from Research Papers #2 and #4. For consistency with the ethanol price assessment, a scenario is assumed whereby no more than 70% of the total juice can be processed by the sugar factory. Fig. 19 compares four optimal portfolio solutions corresponding to regulated electricity prices between US$50–80/MWh, where several operational and investment strategies may be distinguished.

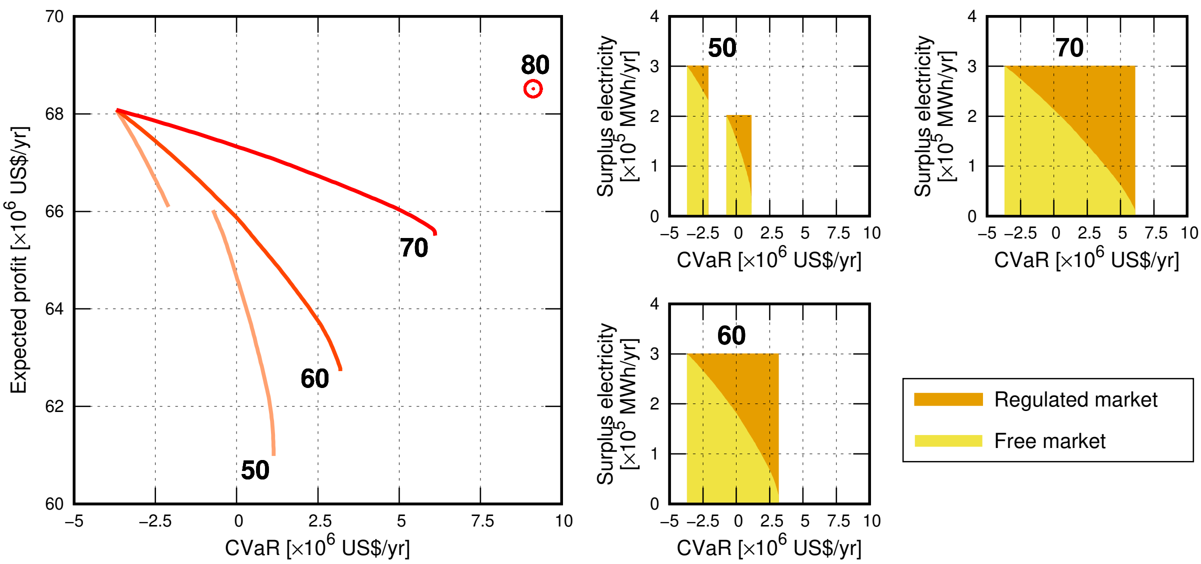

Figure 19 – Comparison between optimal portfolio solutions with electricity prices in the regulated market between US$50-80/MWh. Main plot (left): Pareto frontier of expected profit versus risk. Secondary plots (right): share of surplus electricity between free and regulated markets under each scenario (Source: Mutran et al, 2020[a]).

Notice that the behaviour of results in Fig 19 is very similiar those seen in Fig14 and Fig. 15. There is again a clear tendency for commercialization in the regulated market for risk-averse profiles, while the free market is preferred in a risk-neutral strategy.

The main discrepancy in the results obtained with the piecewise linear model in comparison with those of Research Paper #2 is the minimum attractive price in the regulated market for the condensation turbine. Instead of a price of ¿US$ 65, the surrogate-based superstructure optimization model now finds that even at a level of about US$ 60 / MWh the investment in upgrading the cogeneration system would be attractive to producers. The causes of those differences in price strategy are two-fold: (i) the fixed-parameter models overestimates the traditional Rankine cycle's generation of surplus power, misleading the decision-maker to an unrealistic expected profit; (ii) Paper #2 had originally considered a fully flexible process, with 100% of its mix of juice being destined to sugar production. Since most Brazilian mills have a process capacity of up to 70% for sugar, and since bioelectricity may be an interesting alternative to reduce risks with ethanol detrimental prices, the regulated price level of US$ 60 / MWh could be used as a parameter by policymakers.

Unfortunately, even at higher levels of bioelectricity, there has been no change in the product mix strategy towards sugar. Thus, based on all these case studies, it is clear that there's still a challenge ahead of policymakers to incentivize biofuels in Brazil. In particular, price incentives don't seem to be very effective in attracting more ethanol production. Instead, such types of policies are more effective in attracting investments to increase energy efficiency in sugarcane mills through other products, such as biogas and bioelectricity.

5 Final remarks and practical implications

This project aimed to develop an optimization framework to improve energy management in sugarcane mills, in order to support product mix and investment decisions. More specifically, the goal of the project is to gain a better understanding of key aspects related to the use of biogas and bioelectricity in the bio-ethanol industry, which are directly related to generation and use of biomass residues, as well as technological routes for their economic application. The thesis was therefore structured as a collection of five papers, that individually addressed the research objectives proposed in the development of the decision-making system for the sugarcane industry.

The first paper was a qualitative research in which a combination of literature review and semi-structured interviews with experts from the sugarcane and energy sectors were performed to gain a better understanding of the future for the main products in the industry — sugar, ethanol, bioelectricity and biogas. There was a clear optimism towards all three energy products, especially as a new national biofuels program — namely, the RenovaBio — is expected to greatly increase the demand for ethanol and indirectly incentivize other energy products in the sugarcane sector. Sugar, in turn, seems to have a less promising path ahead, as a consequence of a new conscience for negative health implications of its consumption in excess.

The interviews also allowed the identification of some particularities of the sector that served as basis for the subsequent model-based assessment. First of all, it is clear that the ethanol business is highly sensitive to policies in the energy sector, having been affected both positively and negatively by them over the past decades. Secondly, flexibility in production is seen as a major component to the success of Brazilian sugarcane mills, especially as price risks play a major role in this business. And finally, this paper showed that there are some relevant technological routes for the biomass residues in the sector – for instance, ethanol 2G, biogas generation and improved bioelectricity generation – and although there's still a great challenge ahead of producers to make them both technically and economically feasible, those projects can benefit from large scale production. Thus, there's a call for a broader view of investments to guarantee energetic and economic efficiency in the future of the sugarcane mills.

Papers #2-#5 compose the four steps of the optimization model development, starting with a simplified initial version of the model, testing the use of artifitial neural networks as surrogates, applying the model to a case of multiple sugarcane mills to assess biogas investments and ending with the application of the surrogate-based superstructure optimization model, in which process interdependencies were considered for the assessment of the three technological routes identified based on Research Article #1 — ethanol 2G, biogas generation and the improved bioelectricity generation system.

With regards of the methodological approach, the application of a qualitative research for the conceptualization step of the modeling process was an interesting tool to enable the development of a more realistic and practical model, and also greatly contributed to the building of the scenario-based assessments that were performed. Another key aspect of this methodological approach was that model complexity was gradually increased, and each modeling step dealt with a different decision-making problem in the sugarcane sector.

From the case studies applied in each one of the four modeling steps, a few conclusions were drawn. First of all, it was seen that the production interdependencies between sugar-ethanol production decisions and biomass availability for energy-related purposes have an important impact on investment decisions in the sugarcane mill, thus for a more reliable decision-making process, they should be considered. In this thesis, a couple of approaches were applied for the solution of this surrogate-based problem — artificial neural networks and piecewise linear approximations — and it was seen that the latter is a more efficient technique for this application of portfolio optimization.

All case studies also confirmed that risks play an important role in the decision-making of sugarcane producers, both regarding production mix and investment decisions. Therefore, price policies practiced in the regulated market of electricity have a relevant impact on the investors' willingness to improve their power generation capacities, as those long-term contracts are not subject to price variations. But it is important to highlight that policymakers still have a great challenge to incentivize this source, since the attractive prices for bioelectricity are above the average prices being practiced for other renewable sources (wind and solar).

It was also generally seen that production decisions based on historical price scenarios present a clear tendency for a sugar-oriented business, producing ethanol only with molasses. This result contradicts the expectation that stakeholders showed in the interviews, and implies that there's still a need for better policies for ethanol in the future. Furthermore, results also evidenced that process flexibility plays a major role in risk mitigation in the sugar-ethanol business, which corroborates with the interviewees perspectives that the introduction of ethanol (and other energy products) was determinant to placing Brazil as a leading country for sugarcane production.

As for the technological routes assessed, it was evidenced that ethanol 2G is still far from being economically feasible, while biogas generation is a very promising option. In terms of economic applications of biogas, the multi-mill case study showed that production and investment decisions are more sensitive to the location of the sugarcane mills — and therefore to the infrastructure available nearby — than to the market conditions. Even so, the most interesting use is for the displacement of the diesel used in the trucks of the sugarcane plantation areas. The other two applications assessed, to be sold as piped gas and to be used for power generation, depend on the size of the mill and on the available infrastructure, and even though there has been some exchange of biomass, biogas generation suggests a more distributed profile.

A key extension of the multi-mill optimization problem would be to assess the sizing of investments (which are non-linear decisions) based on the possibility of exchanging biomass among mills. Another potential follow-up research would be to develop a multi-period optimization model to assess the investment options over all years in which the investment costs will be applied, since in this project the investments were expressed as equivalent annual costs for simplification.

In conclusion, this project fulfilled its research goal of developing a more reliable decision-making system to assist policymakers and producers and support bioenergy investment decisions in the sugarcane sector.

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APPENDIX A – Strength in diversity? Past dynamics and future drivers affecting demand for sugar, ethanol, biogas and bioelectricity from Brazil's sugarcane sector

Hughes, N., Mutran, V.M., Tomei, J., Ribeiro, C.O., Nascimento, C.A.O. Strength in diversity? Past dynamics and future drivers affecting demand for sugar, ethanol, biogas and bioelectricity from Brazil's sugarcane sector. Biomass and Bioenergy 2020; 141: 105676.

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Research paper

Strength in diversity? Past dynamics and future drivers affecting demand for sugar, ethanol, biogas and bioelectricity from Brazil's sugarcane sector

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APPENDIX B – Risk-conscious approach to optimizing bioenergy investments in the Brazilian sugarcane industry

Mutran, V.M., Ribeiro, C.O., Nascimento, C.A.O, Chachuat, B. Risk-conscious approach to optimizing bioenergy investments in the Brazilian sugarcane industry. Computer Aided Chemical Engineering 2019; 46: 361-366.

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Risk-conscious approach to optimizing bioenergy investments in the Brazilian sugarcane industry

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Abstract

Deciding price policies in order to attract new investments on renewable energy generation remains a challenge to many public policy-makers. This is particularly relevant to the Brazilian sugarcane industry, which has experienced a significant reduction in new bioenergy projects in recent years. Since investment costs thereof are expressive, a producer's willingness to increase energy generation is highly dependent on market conditions. Herein, we propose an optimization model based on portfolio theory to assess different price policies for attracting investment, where historical variations in sugar, ethanol and spot-market electricity prices are accounted for. Results obtained on a representative case study highlight the significant role played by regulated market prices in mitigating financial risks in the sugarcane business. The analysis enables a better understanding of investors' behavior according to their aversion to risk. It could support policy-makers with more effective pricing in the regulated market to keep promoting bioenergy generation.

Keywords: sugarcane, bioenergy, portfolio optimization, risk analysis, CVaR

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APPENDIX C – Bioenergy investments in sugarcane mills: an approach combining portfolio theory with neural networks

Mutran, V.M., Ribeiro, C.O., Nascimento, C.A.O, Rego, E.E. Bioenergy investments in sugarcane mills: an approach combining portfolio theory with neural networks. Computer Aided Chemical Engineering 2018; 44: 967-972.

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Bioenergy investments in sugarcane mills: an approach combining portfolio theory with neural networks

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Abstract

Investments to increase bioenergy generation have been discussed in the sugarcane industry, as public policies opened a broad range of opportunities for bioelectricity in Brazil. The investment decisions are usually based on market conditions, while those projects may implicate relevant changes in product mix decisions and the process conditions in mills. Thus, this study aims to address the nonlinearities associated to process modeling by an optimization framework combining portfolio theory with artificial neural networks, a widely used approach to approximate functions. The results indicate that changes in process conditions impact decision-making for investments. In conclusion, this study evidences the importance of considering process conditions for optimal economic decisions.

Keywords: sugarcane, portfolio optimization, neural networks.

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APPENDIX D – Biogas in the Brazilian Sugarcane Industry: addressing logistic and economic challenges

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Biogas in the Brazilian Sugarcane Industry: Addressing Logistic and Economic Challenges

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ABSTRACT

Brazil presented an increasing ethanol production over the past decades, resulting in a relevant growth of waste generation. Among the main biomass residues, bagasse, straw and vinasse are the most important, mainly due to their energetic potential. In this context, their possible use for biogas production has been widely examined in literature as an alternative to improve the energy recovery from wastes in the sugarcane industry. Nonetheless, the restrictions associated to the gas sector, including high investment costs and limited infrastructure of pipelines, imply that the economic feasibility of biogas projects may depend on large-scale production. Since the average capacity of refineries in Brazil hinders such level of investments, a possible alternative to guarantee feasibility is to examine the interactions among different refineries for the exchange of biomass products, such as bagasse, which is already a common practice in the industry. This paper proposes an optimization model based on Portfolio Theory, to address the production mix, logistic and investment decisions in a cluster of sugarcane mills in Brazil. The main objective is to improve decision-making of producers by taking into account logistic and infrastructure aspects that are inherent in the sector. The model was applied in a case study of three existing sugarcane biorefineries located in the State of Sao Paulo. Results evidence that the potential uses of biogas are strongly depended on the existing infrastructure for pipelines. Another key insight was that the choice of technological routes is sensitive to the mill's location and size, but it was not strongly affected by price policies in the power sector. Finally, the use of biogas as a substitute for diesel in transportation of sugarcane stands out as an interesting alternative, regardless of the mill's characteristics.

KEYWORDS

Portfolio optimization, Risk, CVaR,Renewable energy, Energy policies, Sugarcane, Biogas

APPENDIX E – Risk-Conscious Optimization Model to Support Bioenergy Investments in the Brazilian Sugarcane Industry

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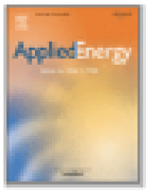

Risk-conscious optimization model to support bioenergy investments in the Brazilian sugarcane industry

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