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PLANNING THE TRANSITION OF BRAZILIAN SUGARCANE MILLS TO ADVANCED BIOREFINERIES USING A METHODOLOGICAL PROPOSAL BASED ON THE INDUSTRIAL SYMBIOSIS APPROACH

Victoria Emilia Neves Santos

Tese de Doutorado apresentada ao Programa de Pós-graduação em Planejamento Energético, COPPE, da Universidade Federal do Rio de Janeiro, como parte dos requisitos necessários à obtenção do título de Doutor em Planejamento Energético.

Orientador: Alessandra Magrini

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"Penso que cumprir a vida seja simplesmente compreender a marcha e ir tocando em frente. Hoje me sinto mais forte. Mais feliz, quem sabe. Só levo a certeza de que muito pouco sei. Ou nada sei.
Ando devagar porque já tive pressa, e levo esse sorriso porque já chorei demais.
" (Almir Sater e Renato Teixeira num momento de grande iluminação)
"An economy based on innovative and cost-efficient use of biomass for the production of both biobased products and bioenergy should be driven by well-developed integrated biorefining systems." (Ed de Jong and Gerfried Jungmeier)
Essa tese é dedicada ao Cosmos, que tudo rege. A Ogum, que me protege. A Yemanjá, que me amadurece. E aos meus pais, aos quais tudo isso se deve.

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PROPOSTA METODOLÓGICA PARA PLANEJAMENTO DA TRANSIÇÃO DE USINAS DE CANA-DE-AÇÚCAR EM BIORREFINARIAS AVANÇADAS USANDO SIMBIOSE INDUSTRIAL: AS PERSPECTIVAS DE UMA VISÃO

Victoria Emilia Neves Santos

Março/2018

Orientador: Alessandra Magrini

Programa: Planejamento Energético

A consolidação da bioeconomia via materialização de conceitos de biorrefinaria reforça a perspectiva de um futuro de processos a base de biomassa. No entanto, apesar do progresso técnico-econômico, ainda existe muito a ser explorado tambem na dimensao socioambiental, especialmente no planejamento da implantação local de biorrefinarias. E é esse o propósito da presente tese.

A Simbiose Industrial (SI) é uma prática que alia a dimensão ambiental com a socioeconômica ao preconizar o intercâmbio de resíduos entre setores que convencionalmente não teriam relação entre si. Nesse sentido, um dos pilares da SI é a inovação. Esta tese examina como se daria a implantação de uma biorrefinaria usando a abordagem da SI e partindo de uma usina de cana-de-açúcar no Brasil. A partir de casos empíricos, esta tese propoe: (1) um modelo teórico conceitual para a transformação de uma usina de cana-de-açúcar convencionais em biorrefinarias avançadas levando em consideração os aspectos locais por meio da abordagem da Simbiose Industrial; e (2) uma metodologia para o planejamento da transição de uma usina de cana-de-açúcar no Brasil que é, em seguida, aplicada a uma usina na região Norte Fluminense (RJ) para a produção de ácido succínico a partir de bagaço.

No curto prazo, 28 novos empregos seriam gerados e 26.939 t de CO_2 ao ano seriam evitadas. No médio prazo, 4 indústrias existentes na região fariam parte da rede de simbiose industrial e, no longo prazo, 4 novas indústrias fariam parte dessa rede contribuindo para a reduzir a emissão de 54.668 t de CO_2 e 283.957 t de resíduos sólidos ao ano.

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Department: Energy Planning

The consolidation of the bioeconomy through the materialization of biorefinery concepts reinforces the prospect of a future of biomass-based processes. However, despite technical and economic progress, there is still much to be explored as well. socio-environmental dimension, especially in the planning of the local of biorefineries. And that is the purpose of this thesis.

Industrial Symbiosis (IS) is a practice that combines the environmental dimension with socioeconomic level by recommending the exchange of waste between sectors that would be conventionally unrelated. In this sense, one of the pillars of IS is the innovation. This thesis examines how the implantation of a biorefinery would take place using the IS approach and starting from a sugarcane mill in Brazil. Building upon empirical experiences, this thesis proposes: (1) a theoretical framework for the transformation of a conventional sugarcane mill into biorefinery through Industrial Symbiosis taking local aspects into account; and (2) a methodology for planning the transition of a sugarcane plant in Brazil, further applied to a plant in the northern region of Rio de Janeiro state (Norte Fluminense) for the production of succinic acid from bagasse.

In the short term, 28 new jobs would be generated and 26,939 tonnes of CO_2 per year would be avoided. In the mid term, 4 existing industries in the region would industrial symbiosis network and, in the long term, 4 new industries would be part of the network contributing to reduce the impact of 54,668 tonnes of CO_2 and 283,957 tonnes of solid waste per year.

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Chapter 1

Introduction

This introduction covers the international and national contexts that motivate and justify the present thesis, providing the elements that make up the knowledge gap addressed. This section also enumerates the research objectives and questions, delimitating the scope of the research and summarizing how it was designed. The main societal and scientific contributions of this study are then presented, after which the thesis' structure is described pointing out where to find the answers to each research question.

1.1 Context and theme rationale

Biorefineries are facilities capable of converting biomass into products ranging from electricity and biofuels to food, polymers and fine chemicals [63]. They promise to drastically change the world's still fossil-based production system [25, 282], while also hastening sustainable development in emerging economies [28, 96, 111].

The biorefinery concept emerged from a confluence of factors. Some of them are the progress of white biotechnology [1]in the last decades, the increasing energy security concerns [114], the environmental restrictions on the use of fossil resources, and businesses' perspective of technological innovation as a way out of the crisis [78].

The biorefinery concept has virtually shaped the develpment of the modern bioeconomy [15, 78]. Its market accounted for US$437.74 billion in 2014 and is expected to reach US$1128.17 billion by 2022 [253]. Biorefineries sum 217 facilities in USA – contributing with US$ 369 billion and 4 million jobs. In Europe, there are 34 facilities — the result of consistent incentive programs [141, 168, 223].

[1]White biotechnology, or industrial biotechnology, is the use of living cells and/or their enzymes to create industrial products that are more easily degradable, require less energy, create less waste during production and sometimes perform better than products created using traditional chemical processes. [114]

In Brazil, biorefining has been essentially tied to food and biofuels production [30, 86]. The country's relevance in this industry lies mostly on its great availability of feedstock. In the season of 2014-2015, for instance, 634 million tonnes of sugarcane were harvested [69], making up 40% of world production [123].

The residual biomass is especially attractive in this context due to its relatively reduced costs and non-competition with food production. Studies of sugarcane bagasse biorefineries in Brazil emphasize technical and economic feasibility analyses [92, 212, 242] and environmental performance evaluation [7, 224, 250]. Regarding the product portfolio, their vast majority focus on energy carriers. As a result, the production of bio-based chemicals still demands further exploration.

Even some of these studies comprising business model analyses [108, 109, 213], very few of them consider either innovative sustainable business models, such as the industrial symbiosis approach [246], or the investigation of future implications of their deployment for local or regional sustainable development.

Industrial symbiosis (IS) is a resource management approach traditionally advocated by the field of Industrial Ecology. More recently, the fields of Circular Economy, Sustainable Innovation and Circular Design also advocated IS as one of its strategies [29, 117, 194]. The industrial symbiosis approach promotes the exchange of residues and by-products among distinct productive activities where one firm's waste becomes another firm's feedstock [60, 292] establishing an industrial ecosystem or a symbiotic industrial network [14].

Since it was coined in 1989, there has been a significant uptake of industrial symbiosis around the world, especially in Europe and China, that has at least 60 industrial ecosystems in operation [245]. However, China's prominence is not representative of the other emerging economies. In a recent study on industrial ecosystems around the world, 68% of the 302 parks assessed were located in Western Europe, and none in Latin America or Africa [188].

In Brazil, IS practices concentrated in projects to improve sustainability practices in industrial clusters. From the eleven cases reported in the literature, three were greenfield [39, 118, 200] and eight were brownfield. Among the brownfield cases, two applied IS principles spontaneously while six concerned planned (and partially implemented) projects [37, 47, 88, 132, 258]. In the agricultural and agro-industrial sectors, some projects of integrated biosystems for hog breeding [27, 45, 190], fish farming [146, 162] and sugarcane farming [209] were conducted in early 2000s. However, none of them addressed the biorefinery concept nor its spillover effects in the surroundings.

The intensification of agricultural and agro-industrial production that followed the 2^{nd} World War has indeed made waste management gain increased attention in agro-industry [177, 251], and the biorefinery concept is also responsive to resource management for considering the integral use of the biomass and its byproducts [36, 193, 199, 232, 254]. This thesis will show that some empirical cases of traditional agro-industries evolved into first generation biorefineries through the implementation of the IS approach [188, 246].

The Bazancourt-Pomacle biorefinery in France, for instance, has been applying industrial symbiosis as a key element of its strategy since the 1990s, reducing its make-up water demand by more than 99% and CO_2 emissions by 67% in the course of 10 years. Also, 1200 direct and 600 indirect jobs were created. In China, the Guangxi Guitang Group obtained environmental and competitive advantages from the use of IS principles in its sugar refinery. Also, the local labor market was altered, reducing brain drain through the financial support to education and research institutes [297].

In 2015, the head of the Bio-based Industries Consortium declared that bioeconomy is "circular by nature" [43] and the biorefinery task of the International Energy Agency (IEA) has among its roles the "promotion of industrial symbiosis for the full sustainable use of biomass" [34]. Hence, the use of the IS approach is apparently crucial to guarantee that all benefits from the biorefinery concept are reaped.

However, both the biorefinery concept and the IS approach are still far from becoming mainstream approaches of industrial development in the modern society. A socio-techno-economic and cultural shift is needed for that to happen. And this is even more evident in emerging economies, where technological and behavioral transitions seems to occur after years of consolidation in the leading knowledge economies.

This thesis focuses in the Brazilian sugarcane industry, responsible for R$152 billion of annual income [50]. Sugar and ethanol are the main products, traditionally attending the food and energy industries respectively. The sector is consolidated and works under this structure for decades. However, ongoing changes might permanently affect its markets in the following years.

Russia decision to become self-sufficient in sugar production [265] — resulting on it net-exporter behavior in the last season [191] — and the abolition of sugar quotas and sugar price-fixing policies in the European Union [255] are setting the world sugar offer to records [271]. Such moves, together with China's expansion of sugarcane crop areas [225] may pose challenges to a giant exporter like Brazil, that has 70% of its production relying on the external market [102].

At the same time, the future of ethanol biofuel will have to cope with vehicles' electrification and with the consolidation of the circular economy that might reduce the demand for ethanol and cars respectively. In the long run, the sharing economy and the product as service paradigms are expected to prevail in urban areas. For instance, in the last 6 years, the sale of electric cars has been growing above 40% annually [207], while carsharing fleet went from 260 to 9,200 vehicles from 2012 to

2015 in emerging economies [286]. Even if these trends are offset by the potential reduction on corn-based ethanol subsidies in the United States, the unfoldings of the present conjuncture are yet very much uncertain [259].

Concerning changes in consumer behavior, it is already acknowleged that the younger generation buys 30% less cars than the older ones [74]. And the same is happening with sugar consumption. In fifteen years in USA and six years in Brazil, people reduced their consumption of soft drinks in 20% due to their high sugar content [41, 98]. Coca-Cola's challenge for scientists to find a subsitute of sugar for its beverages [195] is a clear evidence that the future of sugar is about to be redefined.

Current sugar and ethanol markets' dynamics are on the verge of a new life, demanding well thought planning and action from its players. In this sense, the bioeconomy perspective is itself both an opportunity and a threat to the Brazilian sugarcane industry. As it is true that it advocates the expansion of sugarcane industry's product portifolio, it is also true that it fosters the production of substitutes for its products from other types of biomass.

1.2 Knowledge gap, objective and research questions

Known experiences of IS practices in the agro-industrial sector concern traditional agro-industrial activities where symbiotic exchanges spontaneously emerged as resource management strategies or as a mean to make the most out of the costs incurred in raw material acquisition. This thesis, in turn, takes a normative approach proposing the planned development of advanced biorefineries in the Brazilian sugarcane sector at the local level.

In the least productive regions, the Brazilian local sugarcane industry and its surroundings have a socioeconomic context very distinc from the European. The need for better labor conditions, job positions and reduction of local pollution are still a reality in the present days, added up the relevance for retaining the socioeconomic and cultural prominence of its renewable-based activities.

In summary, the perspectives around the sugar and ethanol markets pose uncertainties in the competitiveness of the traditional sugarcane industry. And it is more critical for the least productive regions in Brazil, comprised of smaller scale facilities that are, thereof, less capable to cope with prices volatility, climate change and further uncertainties. In this sense, the biorefinery concept and the modern bioeconomy seem to offer promissing alternatives for such contexts. However, while the biorefinery concept is theoretically well aligned with the industrial symbiosis approach, empirical cases are still scarce and centralized in Europe, implying that pathways for similar developments in Brazil are still about to be explored.

This thesis then proposes a new arrangement for the local Brazilian sugarcane industry uniting the biorefinery concept and the industrial symbiosis approach. Actually, it is a larger and improved version of the paper Santos and Magrini (2018) [240]. It proposes the development of advanced biorefineries from existing sugarcane mills through the deployment of agro-industrial symbiosis networks. These systems are here referred to as industrial symbiosis-based biorefineries or IS-based biorefineries. The hypothesis is that the deployment of IS-based biorefineries in the Brazilian agro-industrial context lead to increased competitiveness while also improving the economic (feedstock remuneration), social (direct jobs), and environmental (residual solids disposal and CO_2 emissions) conditions of the surroundings.

The questions addressed are:

1. Under which circumstances an IS-based biorefinery can improve the socioeconomic and environmental conditions of a given agro-industrial sector and its surroundings?

2. Which configurations would display the network of an IS-based biorefinery in the least productive regions of the Brazilian sugarcane sector?

The main purpose of this research is to provide an alternative perspective to the Brazilian sugarcane industry taking into account the particular regional and local contexts, while also contributing to the design of healthier productive arrangements where people, environment and agro-industrial activities are mutually benefited from the local consolidation of the modern bioeconomy.

1.3 Research scope and design

Research scope

This thesis is positioned in the field of semi-qualitative exploratory research. It takes a normative approach departing from a desired advanced biorefinery technology to propose how the transition can happen based on empirical cases. This thesis then comprises a conceptual framework to sistematize the process of the desired transition and a methodological proposal to plan the transition of Brazilian sugarcane mills.

Still, it is worth to point out what this thesis is not. It is neither a feasibility analysis, nor an optimization study. It consists of a theoretical assessment based on the literature and on local context data. In the case study, it departs from what is considered as a promising biorefinery configuration in the literature and conceives development perspectives for it in the local level using the methodological approach proposed. Ultimately, it provides frames construct for the development of biorefineries in Brazil using the industrial symbiosis approach.

Research design

The research starts with the identification of empirical cases of industrial symbiosis-based biorefineries from the industrial symbiosis literature. Their development processes are then scrutinized to constitute the conceptual framework. Using the framework and building upon earlier developments on planning industrial ecosystems in Brazil, the methodological approach using scenarios' development is proposed to plan the transformation of an existing agro-industries into IS-based biorefineries. A case study is then performed for the sugarcane sector of the Norte Fluminense region in the Rio de Janeiro state to validate the methodology developed.

1.4 Societal and scientific contributions

Scientific contribution

The scientific contributions of the present thesis are: (1) the conceptual framework that explains how simple sugar refineries emerge to biorefineries from the implementation of the industrial symbiosis approach; and (2) the methodological proposal for planning the transition of Brazilian sugarcane industries to advanced biorefineries using the framework conceived. These developments are original contributions to the biorefinery and industrial symbiosis scientific fields.

Societal contribution

There are issues in the transition to sustainable and socially just bio-based value chains, especially in emerging economies. The progress of modern bio-based economy relies on the competitiveness of biorefining technologies but also on how well they cope with societal needs [241]. Product portfolio and positive spillovers to the surroundings are important elements in this equation.

Brazilian traditional agro-industry historically co-exists with serious social and environmental issues. And it can be argued that it was a matter of design, since its development has been conducted with no such focus. On the other hand, the bio-based transition the world is going through brings the opportunity to shape the modern bioeconomy, making it sustainable and socially just "by design". This thesis then proposes a methodological approach to enable the sistematic development of scenarios for the deployment of biorefineries taking into consideration the local context and allowing their sustainable and socially sound establishment *by design*.

1.5 Structure of the thesis

In the following chapter (Chapter 2), we present the conceptual backgrounds for the research perfomed. In the Chapter 3, the conceptual framework is conceived. Here, the question one is first explored leaning on empirical cases. In Chapter 4, we explain the methodology developed, describing the methods and tools used. The case study is then presented in Chapter 5, exploring question one while also comprehending a building the block to the answer of question two. The following chapter amplifies the discussion of the main outcomes obtained with the case study (Chapter 6), while the conclusions (Chapter 7) redeem the research questions, summarizing the answers provided throughout the thesis, and states the steps foreseen for the continuity and improvement of the research.

Chapter 2

Conceptual background

This chapter presents the main concepts used in this thesis, explaining their origins and typologies and how they are approached in the present research.

2.1 The biorefinery concept

According to the International Energy Agency (IEA), biorefining is the sustainable processing of biomass for the production of a range of marketable bioproducts and bioenergy [152]. Cherubini (2010) and Horta Nogueira et al. (2008) define a biorefinery as an integrated complex of processes and equipment capable of producing different products based on different biomasses, and hence involving a broad range of possibilities in terms of feedstocks, technological routes and products [63, 149]. In this thesis, a biorefinery refers to an industrial facility dedicated to biomass feedstock that produces a range of products (energy carriers, food and intermediate chemicals) through a series of processes.

In terms of source, the biorefinery feedstock can be either from farming (e.g. dedicated crops and manure), aquaculture (algae), planted forests; industry (e.g. leftovers and process waste) and urban areas (sewage and municipal solid waste) [15, 63]. In terms of composition and structure the inputs are mainly oleaginous, starchy or lignocellulosic [63] and, in terms of usability, a biorefinery feedstock can be either residual or virgin material.

Studies on the use of residual biomass have gained relevance in comparison to other feedstocks due to its specific attributes, like (1) non-competion with food production; (2) lower production costs, which also implicates in lower prices; and (3) reduction of costs with waste disposal [121].

Regarding the technological processes, their purposes in a biorefinery are essentially to extract (pre-treat) and convert carbohydrates, oils, lignin and other materials from the biomass [282]. In the case of the lignocellulosic biomass, steam explosion, acid hydrolysis and enzymatic hydrolysis are the most common pre-treatment technologies [15, 149, 216],while conversion technologies can be chemical (e.g., hydrolysis, transesterification), biochemical (e.g., fermentation, anaerobic digestion) or thermochemical (e.g., gasification, pyrolysis, liquefaction, combustion) [63, 64].

The product portfolio is of major relevance to a biorefinery. Some researchers argue that the co-production of commodities and higher added value products is the best strategy for biorefineries, as it may provide higher competitiveness to the energy products [1][19, 121, 277]. Adding to that, Bozell and Petersen (2010), Fahd et al. (2012), Kamm and Kamm (2004) have ranked biorefining products and reported that materials and chemicals have higher added value than electricity and biofuels [35, 121, 165]. Even so, there is still a strong energy bias in most of the biorefining literature.

Bio-platform molecules are an especially relevant category of chemicals. They consist of oxygenated chemical intermediates of which multiple functional groups allow their conversion into a wide range of new and valuable families of molecules [282]. According to Bozell and Petersen (2010) and Werpy and Petersen (2004), bio-platform molecules are mainly organic acids, of which the succinic acid is especially attractive [35, 282]. It is a dicarboxylic acid composed of four carbon atoms and a carboxyl group (-COOH) at each extremity.

Obtainable both from petrochemical and biochemical routes, it acts as a platform chemical [2], capable of being used as surfactant agent, intermediate for antibiotics production and chelating ion for corrosion prevention and other applications [23, 294]. Its peculiar atractivity is related to: (1) its capability to be converted into at least 30 distinct products [238, 239]; (2) the consumption of CO_2 in its fermentative production [67, 244]; and (3) the positive theoretical carbon balance of the fermentation due to CO_2 consumption [33, 275].

The mainly envisioned markets for the succinic acid in the short term are butanediol (BDO), poly butylene succinate (PBS) and polyurethanes production [13, 158]. In the route considered in this thesis [244], succinic acid is obtained biochemically. The existing commercial plants sell succinic acid for US$ 2,860-3,000 per tonne [13, 22, 280]. Furthermore, a previous study by the author and colleagues has shown that the production of bio-based succinic acid, in comparison to other technological routes, was the most competitive in terms of minimum selling price (US$ 0.57/kg), with a relatively high profit margin [237].

[1] As a matter of fact, the author and colleagues are currently investigating the effect of the co-production of succinic acid in the competitiveness of ethanol in a typical sugarcane mill in Brazil.

[2] Bioplatform molecules (bPM) are an especially relevant category of chemical products because of their broad market perspective. They consist of oxygenated chemical intermediates having multiple functional groups that allow them to be converted into new and valuable families of molecules. Usually, these molecules are also 'construction blocks', which means they are also considered monomers, not changing their structure to originate new products [35, 63, 238, 282].

2.1.1 Historical background of the biorefinery concept

Until mid-1980's the term biorefinery was mostly related to the biotechnology-based treatment of fossil fuels. It encompassed the enzymatic treatment of lignite [283], the use of microorganisms as biocatalysts in the removal of sulfur and nitrogen from oil streams [119] and the addition of biomass to petroleum refineries' streams. Up to this period, the biomass processing was referred to as *milling* and it was mainly directed to the food and feed production [198].

The reduction of economic efficiency of agricultural activities due to increasing energy prices and the environmental concerns that started to rise in the 1980's [198] instigated the investigation of strategies for better use of agricultural raw materials, reaping the value of the whole plants and gradually introducing them in non-food markets [227]. This shift was first expressed in the concept of *Agricultural Refineries* [197, 198, 227]. The goal was then to achieve the integrated use of all components of the lignocellulosic material [91] and obtain products with improved value [91, 198].

The term *biorefinery* was only used in this context by 1987 [228], as an acronym of *biomass refinery*[91], to designate the broader possibilities of biomass use brought about by the use of its lignocellulosic fraction. From this period on, white biotechnology took off and a multiplicity of approaches to define a biorefinery emerged. The concepts varied in terms of type of feedstock [208], process flexibility (capability to process one or more types of feedstock) [16, 164, 179], process distribution (centralized or decentralized) [16, 197] and products (food, energy carriers, materials, chemicals) [219]. And *biorefining* became the overarching term for the set of processes that occur into the biorefineries.

2.1.2 Identifying the biorefinery concept

As time passed, more classifications were provided to biorefineries. In the early periods, when the "biorefinery approach" [228] was developed, the main attributes reported for biorefineries were its integrated nature — related to the bioprocessing of the whole parts of the biomass — and its decentralized nature in opposition to the centralization of the O&G industry [198].

Later on, biorefineries were classified according to the:

- type of feedstock I: *whole crop* biorefinery (cereals and maize); *green crop* biorefinery (using "wet biomass" like green grass and sugarcane); and *lignocellulosic* biorefinery (naturally dry biomass like straw) [164];
- type of feedstock II:first, second and third generation biorefineries. First generation biorefinery is that converting edible biomass (starch, sugar, vegetable oil, etc.) into desirable products. Second generation is the biorefinery that

fractionates lignocellulosic biomass and convert its components into desired products, while third generation biorefinery is that obtaining products from algae.

- flexibility of the process in terms of the types of feedstock and products that can be obtained from the process: *phase I* biorefinery (low flexibility with fixed feedstock type and fixed yield of products); *phase II* biorefinery (some flexibility with fixed type of feedstock but more flexibility in terms of product types and yields); and *phase III* biorefinery (capable of processing different types of feedstock and of flexibly producing a wider variety of product) [165];

- technological maturity of the process: *conventional* biorefinery, running on commercial and mature technologies and *advanced* biorefinery, of which technologies are still under develpment stages. Conventional biorefineries are also know as first generation biorefineries, while advanced biorefineries can be subdivided into second generation (mainly lignocellulosic processing technologies) and third generation (mainly algae-based processes) [95];

- main type of conversion process: *biochemical* and *thermochemical* biorefineries [100, 150].

To cope with such diversity of biorefineries and simplify their identification, a classification (or naming) standard has been developed by the IEA Task Force 42 [161]. The main premisse is that the biorefinery concept can not be defined by one of these aspects only. For instance, a facility described as a sugarcane biorefinery does not provide a complete definition of which biorefinery concept it is. Instead, it refers to a set of biorefinery concepts that have sugarcane as their feedstock.

According to this IEA's standard, a set of informations must be provided in order to identify a biorefinery concept. These informations are the feedstocks, the platforms involved, the processes, and the products [95, 161], which are defined below:

- **Feedstocks:** the biomass to be processed by the biorefinery.

- **Platforms:** intermediary products [3]of a biorefinery, for instance, C5 or C6 sugars, syngas, biogas, etc. They are referred to as platforms because they are expected to connect different biorefinery concepts. The number of platforms in a biorefinery concept is an indication of its complexity.

- **Processes:** the processes refer to the [feedstock] pre-treatment and [platform] conversion processes.

- **Products:** the final products from a biorefining facility (energy carriers, food, chemicals, materials, the very platform, etc.).

The naming convention defines a biorefinery by stating the platform, feedstcok, products and then the processes in the this order. Since the platform and products already inform about the process that might be involved, it is common to omit this part of the description.

Hence, a biorefinery is different from a biorefinery concept. A biorefinery refers to the overal idea of an industrial facility that consumes biomass and that through a series of unit operations processes and converts the biomass into a set of products. A biorefinery concept, in turn, is the specific technological description of a biorefining unit and is defined in terms of its feedstocks, platforms, products and processes.

This conclusion is itself the result of the evolutionary dynamic of the field since "the biorefinery concept" has been used to refer to the innovative and emerging notion of having biomass as a substitute of O&G in the provision modern society's goods and services.

2.1.3 Brazilian sugarcane mills as biorefineries

Brazilian sugarcane mills, set aside their size, have similar production processes. A typical description of a sugarcane mill in Brazil is that of a facility that receives the sugarcane, cleanses it, grinds it to extract the juice, cooks the juice to produce molasses and obtain sugar, and finally ferment and distills the remaining molasses (and part of the juice) to obtain ethanol. The fibrous fraction (bagasse) from the grinding stage is burned to produce heat and electricity.

Since it consists on a production process that consumes biomass to produce different products, it can be considered as a biorefinery. It is then useful to characterize it in terms of the categories presented in section 2.1.2. In terms of feedstock, a typical sugarcane mill in Brazil can be described as a green crop, first generation biorefinery. In terms of process flexibility, it is a phase II biorefinery. The yield of sugar and ethanol can be modified depending on the market. Finally, since it is a mature technology, it is classfied as a conventional biorefinery running on biochemical and thermochemical processes.

According to the IEA definition, its concept can be defined as 2-platform (C6 sugar, electricity&heat) biorefinery using sugarcane for crystal sugar, ethanol, electricity and heat. Despite making use of the bagasse (a lignocellulosic material), it can not be considered an advanced biorefinery since bagasse is not separated into its components for further conversion.

[3]Platforms might also act as final products though.

2.2 The industrial symbiosis approach

Industrial symbiosis (IS) has become a key element of new sustainability paradigms beyond the field of Industrial Ecology. It is straightforward in its meaning preconizing the mutually beneficial coexistence of distinct industrial activities by means of resource exchange. As a result, the fields of Circular Economy, Sustainable Innovation and Circular Design also advocates IS as one of its strategies [29, 117, 194].

In an IS network, one firm's waste becomes another firm's feedstock [60, 292] establishing an industrial ecosystem or a symbiotic industrial network [14]. Currently, the approach has broadened to also encompass the exchange or sharing of other (non-residual) resources like knowledge and infrastructure. The goal is to cooperatively achieve ecologically sustainable and economically competitive industrial activity [58].

Despite the protagonism of academy in the promotion of Industrial Symbiosis worldwide, it is essentially a practical approach. The studies on Industrial Symbiosis aim to expand the knowledge base for its effective materialization. This is specially relevant for policymaking so that besides spontaneous and unplanned endeavours, the emergence of IS networks can also be a response to public policies.

Kalundborg symbiosis in Denmark and the Kwinana symbiosis in Austratia are examples of long-lasting experiences of unplanned and self-organized IS networks, while the National Industrial Symbiosis Programme (NISP)[4]in the United Kingdom (UK), the Circular Economy policy in China and Eco-Industrial Parks Program in Korea are examples of durable policies that led to the development of IS networks in their territory.

In Brazil, the state of Minas Gerais, implemented the Industrial Symbiosis Program of Minas Gerais (Programa Mineiro de Simbiose Industrial, in portuguese). Rooted on the NISP methodology, it has involved 317 firms, contributing to avoid the disposal of 140 thousand tonnes residues in landfills and the use of 195 thousand tonnes of virgin resources. Also, 87 thousand tonnes of greenhouse gases (GHG) emissions and 13.6 million m^3 of watershed water [97].

In this section, we are going to cover the historical background of the industrial symbiosis concept, explain the taxonomy that is relevant for this study and introduce the issue of IS at the small scale.

[4]NISP's approach is based on the creation of a residues' market so that the waste exchanges developed were not necessarily permanent. The commercial relationships created were flexible not necessarily demanding the construction of dedicated infrastructure for them to happen [159]. This condition makes it a particular type of symbiosis in which the continuity of the exchanges are more conjunctural than structural. There are other cases where the same remark is valid [75].

2.2.1 Historical background of the industrial symbiosis approach

There has been some debates over the originality of the idea under the definition of the industrial symbiosis approach [31, 32, 105]. Some authors claim that industrial symbiosis is far from new. Waste exchanges between originally unrelated firms trace back to the 19th century. The notion of this practice as something aimed at mimetizing nature's zero waste attribute would also be ancient. Cases of by-product development in the coal gas, iron making (slag), and synthetic dyes industries have been reported in sectoral and scientific magazines since 1862 [247] *apud* [103]. Interestingly, the American Industrial Waste Trade Industry Association already existed in 1913 [103].

These evidences point out at the historical nature of providing valuable use for industrial residues. However, such seminal market-headed initiatives had not the environmental dimension as a co-motivating point so that closing the cycle [31]. Neither implied the global uptake of such practices, which were carried out mainly in England, Germany and the United States [32].

Industrial Ecology stems from the article of Frosh and Gallapoulos in Scientific American, “Strategies for Manufacturing” in 1989 [135]. These former General Motors' engineers presented industrial processes as organisms with metabolisms and suggested the development an "industrial ecosystems" in an analogy with ecological systems [135]. From that publication, academics and practitioners from the United States leveraged Industrial Ecology as a scientific field in engineering [17, 140].

The term Industrial Symbiosis is reported as been first used in 1989 by Inge Christensen, a pharmacist, and her husband, Valdemar Christensen, the Kalundborg power plant manager, to describe the process carried out in Kalundborg [62]. Ever since, in the quest to materialize successful and long-standing IS networks, major efforts have been expended to uncover existing cases of IS networks worldwide [3, 61, 178] and to account the outcomes from such developments [157, 186, 274].

Despite the challenging implementation process, the IS approach has driven local and regional sustainable development [106, 107], besides the environmental benefits. Such outcomes are mainly due to innovation and new businesses creation [174, 192], new and better employment opportunities [145, 297], educational background improvement [297], and the encouragement of sustainable policies [53, 126]. The use of IS as a sustainable business model strategy has also been addressed recently [160, 214**?**]

2.2.2 Taxonomy of IS networks

The uptake of the IS approach in different contexts and the uncovering of existing of IS networks have revealed distinct avenues for the materialization of IS systems. In this thesis, these distinctions are explained in terms of taxonomies. A set of aspects are considered: exchange boundaries, firms location, initialization pattern, facilitation level.

Exchange boundaries refer to whether the byproduct exchange occurs inside or outside the firm boundaries. It is designated *internal symbiosis* when exchanges are intra-firm and *external symbiosis* when they are inter-firm [60, 148, 246]. When considering the location of firms, the IS network can be either colocated or not colocated [60]. Colocated firms comprise those established in a delimited industrial district or park, while not colocated firms do not share the same site.

The initialization pattern regards the starting event (or "seed") of the symbiotic network. At least three possibilities have been identified: (1) pre-existing waste exchanges between firms; (2) former partnerships between firms to approach common issues; and (3) the existence of "anchor tenants" providing a critical mass for the network emerge [60].

The facilitation level comprises the existence of a third party to conduct or coordinate the IS network development. Under this perspective, the emergency of an IS network can be either facilitated or self-organized [176, 296]. Facilitated IS networks can be either planned or unplanned [296]. Unplanned IS networks are those without a previous design to define its development [93, 241], which can arise either spontaneously or fostered by public policies or other regulatory instruments [131, 257].

2.2.3 Industrial symbiosis at the small scale

Smaller scale enterprises are likely to play a major role in the future society. Small farms are considered key to poverty alleviation, sustainability, and food security. They are also crucial to achieve the 70% increase needed in food production to keep up with the urbanization of the world by 2050 [154]. In emerging economies, small and medium enterprises (SMEs) are responsible for 45% of formal employment and 33% of national income [24, 172], while small farms supply 80% of food consumed [155]. In Latin America, for instance, there are nearly 13,7 million micro, small and medium enterprises [172], while 35% of total cultivated land is occupied by smallholder farmers [155].

Sustainability is crucial for SMEs and small farms to thrive. Their resilience is a function of how they create long-term financial value, reduce negative environmental impacts and contribute to social change [153, 252]. Industrial symbiosis (IS) have proven to be successful for addressing waste management and avoiding environmental impacts of large scale, material and energy-intensive industries, existing an extensive literature on the knowledge created [18, 61, 117, 297]. However, in the small scale, it has not received comparable coverage from IS practitioners and researchers.

As this thesis focuses on smaller scale sugarcane mills (characteristic of least productive regions in Brazil), this section provides a literature review of industrial symbiosis in the small scale to situate the research. The questions that guide this phase are (1) Why did the respective authors have chosen to focus IS for the small scale IS? (2) What are the contributions provided by existing literature on small scale IS? (3) What the authors consider to be small scale?

It provides a comprehension of how the industrial symbiosis has been understood at the small scale. The literature was selected from a keywords-based survey on scientific databases (Web of Science and Scopus databases and Google Scholar). Two groups of keywords were established with group A representing the IS approach and group B representing the notion of small scale. Further these groups were combined in an 'AB' heuristic (Figure 2.1). Keywords of group A preceded by 'local' where also considered.

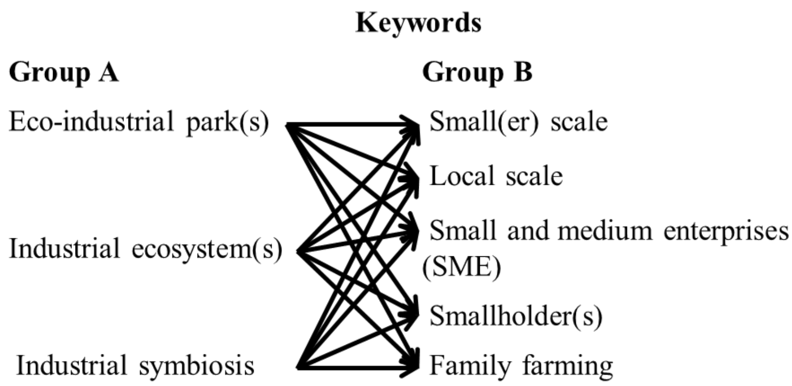

Figure 2.1: Keywords used in combination 'A' and 'B'.

Thirty publications were retrieved. In a preliminary screening of title & abstract, 11 were withdrawn for being either inconclusive regarding the small scale aspect or for not addressing the issue of small scale. Hence, the material underpinning this review comprises 19 publications, which are mainly studies concerning Europe. Empirical cases has been reported from Austria [101], Finland [263], Germany [101], Greece [48, 183], Italy [73, 84], Netherlands [173], Portugal [101], Romania [101], Spain [80, 101], Sweden [284] and UK [101, 159, 260], while hypothetical cases were collected from Italy [1] and Sweden [230].

Empirical cases from Canada [173, 175], China [139], India [55], Japan [57] and

Liberia [11], and a theoretical analysis of industrial ecosystems [127] also make up the literature considered.

At least four distinct deliberate reasons were identified and classified: (1) to contribute on such a poorly investigated topic; (2) to meet a specific criteria; (3) to push local development; and (4) to improve IS performance. Also, 4 in the 19 studies (21%) addressed the small scale for no special reason. Half of the studies were motivated by the limited coverage of IS on the small scale in the scientific literature.

Besides the motivation, we were also interested on the main contribution each study provided to field. Five distinct contributions were observed: identification and discussion of opportunities and challenges; taxonomies; innovative strategies; tools; and performance assessment.

Opportunities and challenges comprise studies that explore alternatives for the deployment of small scale IS. Taxonomies cover studies providing descriptions and classification considering small scale IS systems. Innovative strategies and tools regard the introduction of new approaches for developing IS on the small scale. Performance assessments comprise the evaluation of the impacts of diversity, scale, recycling boundaries and type of waste on IS projects. In the following paragraphs the respective studies are detailed.

Opportunities and challenges Chronologically, the first to point the the gap of small scale IS were Lambert and Boons (2002) and LeBreton et al. (2004) [173, 175]. Leaning on industrial parks composed mainly of SMEs (so-called 'mixed industrial parks'), the former discuss possibilities for developing more sustainable approaches under the perspective of eco-industrial parks (EIP). Despite the poor process integration and collaborative behavior among SMEs, the authors suggest that new ideas are more likely to emerge in eco-industrial parks due to the concentration and diversity of firms. LeBreton et al. (2004) provide a similar approach without focusing on industrial parks [175]. Ristola and Mirata provided, some years later, insights for the development of smaller scale IS by the integration of local paper recycling, waste management and energy production systems [230].

Diverting from the prevailing urban/industrial focus, Alfaro and Miller (2014) draw attention on opportunities for applying IS principles to smallholder farming [11]. They link IS and integrated farming research (IFR) to increase farm production while also minimizing wastes. Abate et al. (2015) presented opportunities and needs for integrating bio and solar refineries, arguing that biorefineries are more competitive on the smaller scale, at regional level, and stating that cooperation with surrounding productions is crucial for bioeconomy development [1]. More recently, Chattopadhyaya et al. (2016) and Manara and Zabaniotou (2016) presented opportunities and challenges for the development of IS on the small scale [55, 183]. They investigated existing and potential IS connections in Muzaffarnagar (India) and alternatives for valorization of glycerol waste streams from small biodiesel plants in Greece respectively.

Taxonomies Fichtner et al. (2004) classify and characterize local IS networks into industrial supplier parks and resource recovery networks [127]. The latter is further divided into networks with and without common investments. The authors consider the latter is appropriate to SMEs. Resource recovery networks without common investments consist on the systematic registration and bundling of all residues for proper utilization. SMEs are more likely to adopt it since individual small firms profit from the joint efforts. More than ten years later, Cecelja et al. (2015) classified industrial activities, resources and process technologies in Greece to develop an ontology of a web service to support IS networks. SMEs were the majority of the firms mapped [48].

Innovative Strategies In 2007, Wolf and colleagues reported a semi-planned strategy to avoid sub-optimization and unhealthy dependencies in the development of local symbiotic networks among a forest industry, a municipality and an energy service company in Sweden [284]. In 2010, a project to find innovative uses for industrial and domestic waste was initiated in North East England and SMEs participation was considered crucial to re-boost the market for recycled material, recognizing them as valuable resources [260]. Based on the European Directive Integrated Pollution Prevention and Control (IPPC) [5], Cristobal Andrade et al. (2012) developed a waste management strategy for atomized SMEs that led to symbiotic relationships and applied it to the printing industry in Spain [80].

Den Boer et al. (2012) present the strategies used at ten initiatives carried out under the European project "ZeroWIN" aimed at "investigating how the closed-loop philosophy can contribute to achieving zero waste by adopting a network approach, and using a combination of methods and tools, technology and design innovations as well as policy measures" [101]. It focused mainly on small and medium scale manufacturing industries. Cutaia et al. (2015) describe the development and implementation of the first Italian platform for IS, created to support SMEs identify opportunities for synergies at regional scale [84]. In the same year, Tsvetkova et al. (2015) proposed a replication framework to leverage the deployment of industrial ecosystems while also achieving "economies of repetition" [263]. According to the authors, the transfer of technical knowledge and business format to new locations would facilitate the organizational learning and the development of collaboration mechanisms. They have applied it to Finish SMEs on the bioenergy sector.

Tools Cortini and Giorgio (2009) describe the Costellazione Apulia's Electronic Platform, a web and mobile phone based platform developed in 2001 to enable the exchange of "production externalities' (information, material, etc.) among 60 Italian SMEs leading to a flexible IS network [73]. Geldermann et al. (2010) presented the concept of Multi-Objective Pinch Analysis (MOPA) for coupling byproduct streams from SMEs for reuse in China [139]. The authors aimed at filling a gap of the Pinch Analysis tool, which is a well-established for plant integration in large chemical installations. Alfaro and Miller (2014) developed an optimization model to evaluate the potential for income generation and waste reduction of IS in smallholder agriculture and applied it to a community development project in Liberia [11]. Cecelja et al. (2015) presented an innovative paradigm for IS using ontology engineering in a multilingual web service to support Industrial Symbiosis networks in Greece [48].

Performance assessments Chen et al (2012) assessed how the scale, recycling boundaries and type of waste influences on IS projects in Japan [57] while Jensen (2016) investigated how geospatial industrial diversity affects regional industrial symbiosis in UK considering also industrial SMEs [159]. In the former, the authors concluded that large-scale projects do not necessarily lead to better performance in terms of virgin material saved and operating rate. In turn, Jensen (2016) found that the higher diversity of industries provides the greatest opportunities for creating local industrial symbioses [159].

The studies are summarized in Table 2.1. In most of them industrial SMEs are the elements of the IS networks, but integrated farming systems (or integrated biological systems) and biorefineries (or biofactories, bioindustries, etc.) are also mentioned.

2.3 Industrial symbiosis and the biorefinery concept

2.3.1 Industrial symbiosis and agro-industry

Nutrient recycling through waste exchange in agricultural and (semi-)industrial activities have been historically performed on the basis of integrated biosystems or integrated farming systems. These regarded small to medium scale farms where different livestock, crop and seafood production were carried out. Indeed, in 2000,

[5] The European Directive Integrated Pollution Prevention and Control (IPPC) originally did not cover SMEs

Table 2.1: Summary table of literature review of industrial symbiosis at the small scale

Publication	Country	Motivation for small scale	Main contribution	Small scale unit
Lambert and Boons (2002) [173]	Canada	Poorly investigated approach	Opportunities and challenges	Mixed-industrial parks
	Netherlands			
Fichtner et al. (2004) [127]	Germany	Fit to specific criteria	Taxonomy	SMEs
LeBreton et al. (2004) [175]	Canada	Poorly investigated approach	Opportunities and challenges	Local businesses
		Positive externalities		
Ristola and Mirata (2007) [230]	Sweden	Poorly investigated approach	Opportunities and challenges	Small-scale production units
		Positive externalities		
Wolf et al. (2007) [284]	Sweden	Not deliberate / unintentional	Strategy	Small and medium-sized forest industries
Cortini and Giorgio (2009) [73]	Italy	Poorly investigated approach	Tool	SMEs
TheEngineer (2010) [260]	UK	Improve IS performance	Strategy	SMEs
Geldermann et al. (2010) [139]	China	Poorly investigated approach	Tool	SMEs
Chen et al. (2012) [57]	Japan	Poorly investigated approach	Performance assessment	Small scale projects
Cristobal Andrade et al. (2012) [80]	Spain	Poorly investigated approach	Strategy	SMEs
Den Boer et al. (2012) [101]	Austria Germany Portugal Spain Romania United Kingdom	Poorly investigated approach	Strategy	Small and medium-sized industries
Alfaro and Miller (2014) [11]	Liberia	Poorly investigated approach	Opportunities and challenges	Smallholder farms /
		Fit to specific criteria	Tool	Integrated farming systems
Abate et al. (2015) [1]	Italy	Fit to specific criteria	Opportunities and challenges	Biorefineries
Cecelja et al., (2015) [48]	Greece	Poorly investigated approach	Taxonomy	SMEs
		Improve IS performance	Tool	
Cutaia et al. (2015) [84]	Italy	Positive externalities	Strategy	SMEs
Tsvetkova et al. (2015) [263]	Finland	Fit to specific criteria	Strategy	SMEs
Chattopadhyaya et al. (2016) [55]	India	Not deliberate / unintentional	Opportunities and challenges	MSMEs
Jensen (2016) [159]	UK	Not deliberate / unintentional	Performance assessment	SMEs
Manara and Zabaniotou (2016) [183]	Greece	Not deliberate / unintentional	Opportunities and challenges	Small-scale biodiesel plants

a seminal work on IS taxonomy, recognized that, when agro-industrial IS networks are formed they comprise integrated biosystems [60].

However, agro-industry has gradually increased its industrial character with production intensification that followed the consolidation of the Oil&Gas sector. Hence, agro-industry here is the physical, biological and/or chemical transformation of agricultural or farming resources in an industrial facility for the production of an specific product or set of products[6].

In 2001, Lowe's Eco-industrial Park Handbook for Asian Developing Countries first acknowledged intensive agriculture and agro-industry in the IS literature [178]. However, empirical cases of long-standing IS networks already included agricultural and/or agro-industrial activities. The seminal experience of Kalundborg included the destination of waste heat from the power plant to fish farms nearby; treated sludge and used yeast from the insulin plant to neighboring farms as fertilizer and feed to pig breeders respectively [116].

Indeed, two formats of long-standing IS networks encompassing agro-industrial activities were observed: those where agro-industry played a central role starting up the IS network (e.g. Guitang Group's sugar refinery in China and British Sugar site in England); and those where agro-industrial firms entered the IS network throughout its development (e.g. Styria in Austria and Najangud in India) [18, 178, 246].

Agro-industry has then been considered in studies on policy instruments for the deployment of IS network [176, 289] and on studies to improve the performance of biofuels production [142, 185, 226]. Recent developments also focus on the fields of

[6] Also referred as agro-processing [5]

urban agriculture [54, 196] and biomanufacturing and biorefining [66, 183].

2.3.2 Symbiotic networks with biorefineries

The literature on industrial symbiosis networks (ISNs) that namely considering biorefineries among its tenants can be categorized into: “empirical case studies”, when existing ISNs are investigated; “hypothetical case studies” when new ISNs are suggested or designed (and where this very thesis is inserted); and “theoretical contributions” when the focus is conceptual, managerial and methodological. Although these categories overlap (since case studies can also provide theoretical and methodological outcomes), we develop each of them along with some examples.

The only empirical case study considering an operating and self-designated biorefinery is the Bazancourt-Pomacle facility in France, also known as the European Biorefinery Institute or Institut Europeén de la Bioraffinerie [241]. Built upon 70 years of activity, this biorefining entity has been applying IS as a key element of its strategy since the 1990s. It led to the development of an eco-industrial estate and of an innovation platform. The synergies were first conducted among farmers and mills, with exchanges of thin juice, sugar syrup, glucose, alcohol, CO_2, water and energy (steam). These synergies later culminated in the creation of high technology firms (also within the symbiotic network): Soliance (molecule developer for the cosmetics industry), Bioamber (bio-based succinic acid producer), Cristanol (bioethanol producer), Air Liquide (for recovery and processing of CO_2) and Wheatoleo (maker of detergents) [241].

A pilot project from Italy considered the development of a biorefining system in the Emilia-Romagna region with the application of IS principles [82, 83, 85]. A participatory approach was used encompassing agro-industries and research laboratories. The companies were responsible for the data about their input and output streams while the labs investigated potential applications.

Regarding the hypothetical case studies, they concern conceptual proposals of biorefineries as elements of ISNs [1, 2, 189, 240] and methods to design and/or optimize ISNs centered on biorefineries [142, 211, 226]. A group from the USA also combined a geographical information system (GIS) and process engineering to design an agricultural industrial ecosystem that processes peanut hulls to produce activated charcoal, hydrogen and resins for adhesives manufacture in Georgia [211].

The studies categorized as theoretical contributions mostly discuss the *nexus* between the IS approach and the biorefinery concept. Three approaches can be distinguished. The first considers the IS as a strategy that can be used by biorefineries to achieve competitiveness [220]. The second sees the IS approach as inseparable from the biorefining concept since the shared premise of integral use of biomass links them conceptually [206, 276] and also because of the relevance of the concepts for reducing natural resource use [8]. The third approach acknowledges the crucial role of renewable-based eco-industrial development in the field of industrial ecology [281]. Wells and Zapata (2012) argue that with the emergence of modern bioeconomy, the industrial ecology should acquire a more proactive, critical and interventionist character, conciliating sustainability science, critical thinking and social equity [281].

More recently, a group from the University of Bordeaux (France) proposed a new branch of industrial ecology named "agro-industrial ecology" [125].They argue that "(i) the strong interactions between farming production processes and the natural environment; (ii) the predominance of diffuse instead of point source pollution in farming operations; (iii) the highly scattered nature of farming enterprises within landscapes; and (iv) the high diversity of farming practices and interactions over time and space" demand that agri-food systems have specific approaches in this scientific field, distinct from purely industrial social-ecological systems.

Making a correspondence with this thesis, it is developed upon the empirical experience that materialized the biorefinery concept from the implementation of the IS approach. It also aligns with the third approach since the methodology conceived regards an instrument for proactive action in terms of the development of scenarios and further application to a local context.

2.3.3 The Brazilian sugarcane industry as an IS network

The Brazilian sugarcane processing facilities, despite traditionally assigned as mills or distilleries, can also be considered as conventional 1st generation biorefineries. In their product portfolio there are sugar and ethanol but also bagasse, filter cake and vinasse which are traditionally used as fuel (bagasse) in the cogeneration and recycled to the sugarcane crops for fertigation (vinasse and filter cake). Mills are the units producing sugar and ethanol in the same site, while distilleries do not produce sugar.

Actually, the now traditional co-production of ethanol was once a new business solution to make use the molasses discarded in final stage of sugar production [221]. Similarly, the production of electricity from bagasse responded to the annoyance caused by the disposal of this abundant byproduct coupled with the demand of more stable energy supply. Brazilian sugarcane mills became self-sufficient in energy since early 1900's [42]. This shows that industrial symbiosis is not an outlandish practice in the sector.

Currently, from the existing 434 sites, 22% produce electricity surplus and obtain extra revenues from selling it to the national grid [203]. Still, the internal recycling of filter cake and vinasse are performed since the 1970's and was intensified from 1999 onwards in response to increased environmental concerns and the rise in exchange rates and prices of conventional fertilizers [233]. However, the pathways towards becoming a sustainable and locally sound advanced biorefinery are still open and its the very purpose of this thesis to contribute with it.

Chapter 3

The emergence of biorefineries from the implementation of the industrial symbiosis approach

From the review of industrial symbiosis experiences, encompassing agro-industrial activities, there were cases where actual biorefineries were created from the implementation of the IS approach. This chapter provides a review of uncovered experiences available in the literature of industrial symbiosis-based biorefining. The goal is to capture the motivation behind their emergence as well to draw a picture of the productive scales, types of synergies, timeline and spillovers of their development processes. The aspects examined are the exogenous and endogenous contexts (following the approach of Schieb et al. (2015) [241]), the evolutionary path and the outcomes for the firms and their surroundings

3.1 Recalling the biorefinery concept

Both industrial symbiosis and biorefining are modern terminologies for practices being performed for decades [61, 104, 169]. Before these terms were coined, multi-product agro-industry was already enabled by the recycling of formerly residual streams in other productive processes, increasing the value obtained from each feedstock and reinforcing the economic stability through diversification of consumer market.

As we could aprehend from the previous section, the kernel of a biorefinery can be epitomized as organic matter getting into an industrial site and leaving it as multiple products. With this in mind, a survey was performed in the IS literature aimed at finding experiences where the application of the IS approach in simple one-feedstcok one-product agro-industries led to the development of systems where organic matter gets into industrial units and leaves as multiple products. That is, where IS led to the development of biorefineries.

The biorefinery concept here is thus that of conventional, 1st generation biorefineries, while the industrial symbiosis approach is that of exhausting the value that can be obtained from the byproducts. To allow comparison with the case investigated in this research, the aspects covered are the role of the agro-industry (if it acted as anchor of the IS network or not), the level of facilitation (if the IS network developed spontaneously or facilitated by an external party), the scale of production (size of the tenants) and the impacts observed in the surroundings. The cases described are summarized in Table 3.1.

Table 3.1: Cases used as reference for developing the conceptual framework

Case	**Country**	**Startup**	**Area (ha)**	**Jobs**	**Feedstock**	**Feedstock Processing capacity (million t/y)**	**Products**
British Sugar	United Kingdom	1925	NA	NA	Sugar beet	3	Sugar products Ethanol CO2 Electricity Lime Tomatoes Animal feed Aggregate for construction Topsoil Betaine Vinasse
Bazancourt-Pomacle	France	1953	160	1800	Sugar beet Wheat Alfalfa	3	Sugar Ethanol CO2 Cosmetic ingredients Succinic acid Surfactants
Guitang Group	China	1956	200	3000	Sugarcane	1	Sugar Ethanol Paper Cement Material for road construction Compound fertilizer

3.2 Selected cases

From what was presented in the previous section, there are plenty experiences of IS networks encompassing agricultural and/or agro-industrial activities. However, when the biorefinery concept is considered, only one empirical case self-designated biorefinery is reported in the literature.

Based on the discussion presented over the identification of biorefinery concept (section 2.1.2), other cases could be included in the realm of industrial networks with biorefineries. Two of them comprise IS-based biorefineries since the implementation of the IS approach was the foundation for the biorefinery development. In the following paragraphs, the three cases are presented pointing out why they constitute IS networks, biorefining facilities and IS-based biorefineries.

The first case is the Bazancourt-Pomacle biorefinery (France), which is a benchmark biorefinery. It is an IS network because byproducts and utilities streams are exchanged among the firms installed in the site becoming raw material for other products. It is a biorefinery because from two biomass feedstocks, several substances are produced attending to different markets. It can also be considered an IS-based biorefinery because the IS approach was the main strategy for its constitution. Without the IS approach, it would not develop as it has.

The second case is the sugar refinery of the Guitang Group (China). In the literature, it is not designated as a biorefinery, but it indeed make use of sugarcane as raw material for multiple products such as sugar and paper. This system constitute and IS-based biorefinery because the exchange of byproducts among the production facilities enabled the development and economic sustainability of this bioindustrial complex.

The third (and last) case investigated is the British Sugar industrial complex at Wissington (England). Its competitiveness and development are due to the orientation of continuously developing valuable uses for their waste streams. This strategy makes it a case of IS-based biorefinery since such developments enabled that from the beet root a diverse product portifolio was created [223]. Table X summarizes the aspects that justify the choice of such cases as foundations for the conceptual framework to be introduced in this chapter.

3.3 Examining the empirical cases: elements for the conceptual framework

In order to abstract a development model for the operationalization of a biorefinery concept from the implementation of the IS approach to a conventional agro-industrial facility, the empirical cases previously presented are used as reference. In the following sections, the exogenous and endogenous contexts as well as the evolutionary path of each case are described. The identification of the exogenous and endogenous contexts is aimed at the comprehension of the factors internal and external to the biorefinery that pushed (or pulled) its development, while the evolutionary path indicates the stages through which such development was carried out.

Bazancourt-Pomacle Biorefinery (France)

The first self-designated industrial symbiosis-based biorefinery is the Bazancourt-Pomacle in France, also known as the European Biorefinery Institute or Institut Europeén de la Bioraffinerie [241]. Owned by Vivescia and Cristal Union, it started in 1953 as a sugar factory in a cooperative effort of sugar beet and wheat farmers.

Exogenous context The exogenous circumnstances under which the Bazancourt-Pomacle biorefinery was created coincides with the period of liberalization of world trade started with the General Agreement on Tariffs and Trade (GATT) in 1947 and the reform of the European Common Agricultural Policy (CAP) after 1962.

The GATT is the international agreement that predated the WTO agreement that established the World Trade Organization (WTO) in 1995 [287]. The GATT refers to a series of international trade agreements designed to promote the reduction of barriers to trade between nations, in particular tariffs and customs duties between the signatory members of the Agreement [156].

The CAP is one of the oldest policies of the European Union (EU). It was created in 1962 to support farmers and ensuring Europe's food security [120]. In the following years, farmers' responsability for environmental protection of local territories also became part of the policy agenda. The main instruments of CAP were direct money transfer in the form of subsidies and obligatory set-aside of land [241]. Such measures led to production surpluses which were addressed with production quotas, but the inclusion of the agricultural sector in GATT and WTO agreements forced the gradual reduction of CAP budget, ending the mandatory set-aside of land and restricting subsidies to exceptional cases only [241].

The reduced protectionism over agricultural production worldwide culminated in the increased price volatility of agricultural products [137, 241]. Such conjucture created a situation of vulnerability of farmers regarding their longer term viability [137].

Endogenous context The origins of Bazancourt-Pomacle biorefinery date back to the eighteenth century. By then, the region was barely productive due to its chalky soil. The area around it was at least 35% more productive. Only by 1950, after a sequence of unsuccessful endeavours and investment on agricultural techniques and equipment, the agricultural production started to improve, leading to the triplication of sugar beet crops from 10,000 ha in 1945 to 30,000 ha in 1952 [241].

In the 1930s, farmers in Champagne who grew sugar beet obtained reasonable yields, but had fragile partnership with surrounding sugar manufacturers. There were no contracts or payment assurance, and commercial relations were tense [241]. Besides that, the existing processing capacity was inferior to the local sugar beet production. Hence, farmers from the cooperative moviment united to turn an existing distillery into a sugar factory as a strategy to reduce their dependence to the manufacturers and increase their income.

The sugar factory that marks the outset of the biorefinery was put into operation in 1953. Since then, a series of mergers and partnerships among farmers and cooperatives have been developing to sustain the agro-industrial sector in the Champagne-Ardenne region, guaranteeing its competitiveness and the livelihood of cooperated members. The farmers' union, later on converted to cooperatives, were crucial to the biorefinery development, since they went beyond farming activities, investing also on downstream processes to add value to their production [241].

Evolutionary path Its first expansion strategy was to create a Research and Development (R&D) firm in 1989. Two years later, an inulin (later on starch) and glucose plant was established, leading to investments on spin-offs that made use of the residual streams generated. With time, partnerships were performed from which further facilities were installed to take advantage of the R&D infrastructure and availability of residual feedstock.

Industrial symbiosis was the strategy that enabled the site to become an internationally recognised integrated biorefinery. Synergies started with material exchanges and then exchanges and joint management of utilities came into place. The biorefinery development was incremental and unplanned — without a previous design which to attain to —, and the synergies were carried out as one of the response-strategies to sustain and develop its activities.

The synergies were first conducted among farmers and mills, with exchanges of thin juice, sugar syrup, glucose, alcohol, CO2, water and energy (steam). These synergies later culminated in the creation of high technology firms (also within the symbiotic network): Soliance (molecule developer for the cosmetics industry), Bioamber (bio-SA producer), Cristanol (bioethanol producer), Air Liquide (for recovery and processing of CO2) and Wheatoleo (maker of detergents) (Schieb et al., 2015).

Currently, Bazancourt-Pomacle biorefinery processes 3 million tonnes of biomass (sugar beet, wheat and alfalfa), with turnover around 600 million euros per year and eleven firms making up the site tenants. These comprise a sugar factory and dehydration plant; a joint research center; a starch and glucose plant; an ethanol producing plant; an industrial demonstrator; a CO_2 collection center; a production and research center for active cosmetics ingredients; a pilot plant for second generation ethanol; and the White Biotechnologies Centre of Excellence, a partnership between three academic institutions (Figure 3.1).

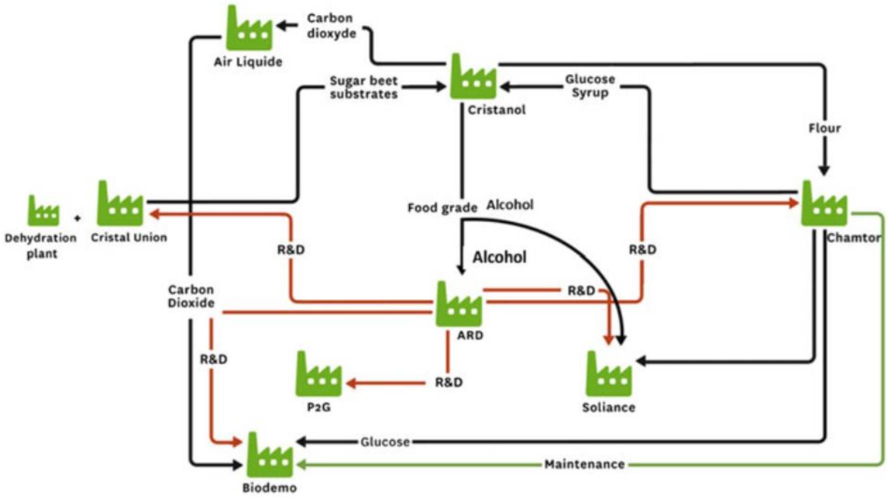

Figure 3.1: Industrial symbiosis of Bazancourt-Pomacle (France). Source: [241].

Outcomes In terms of outcomes to the surroundings, the cooperative movement and the biorefinery development completely transformed the Champagne-Ardenne region. Earlier considered a "flea-ridden desert" with second-rate agriculture [241], in 2005 it was considered a world class industrial cluster and currently houses the second largest maize processor and fifth largest sugar producer in Europe [241].

Besides the job positions created in the region, the biorefinery was turned into a knowledge and innovation pole, creating a local network of competences with the R&D center ARD (Agro-industries Recherches et Developpements (Agro-Industry Research and Develpment) and academic institutions in the Centre of Excellence for White Biotechnology (CEBB).

Guitang Group's sugar refinery (China)

The sugar refinery of the Guitang Group (GG) is a well-studied case of stable and long-term developed industrial symbiosis [61, 178, 295]. Established in 1956, it was formely state-owned and, from 2001 on, became part of the Shenzhen Huaqiang Holdings Co. Ltd. [59]. Despite not self-designated a biorefinery, GG's sugar refinery can be considered as such since the industrial complex produces sugar, ethanol, paper, compound fertilizer and cement from sugarcane. Industrial symbiosis performed through recycling of alkali, CO_2, sludge, ash, pith, gypsum and bagasse enabled such product diversity [297].

Exogenous context The exogenous context of GG's sugar refinery coincides with a liberalization period of Chinese economy. Internally, GG's sugar refinery establishment crossed two distinct phases of the Chinese politics and economics. It started operating in the Mao Tse Tung's comunist government (1947-1976), further developed during the "Market Socialism" of Deng Xiaoping (1976-1993) and was privatized in the government of Jiang Zemin (1993-2003) [38]. Internationally, the GATT agreement was already in force and China was also one of its signataries [288].

Differently from the Bazancourt-Pomacle biorefinery, feedstock producers (i.e. the farmers) are external to GG's sugar refinery, making part of the exogenous context. The sugarcane farmers of the region are mainly smallholders that produce an average of 1,500 tonnes of sugarcane per year [178]. A scenario of instability of prices threatens the attractivity of sugarcane plantation so that the IS strategy of GG encompassed the strenghening of the partnerships with feedstock suppliers.

Endogenous context The studies covering GG's sugar refinery development suggest that the motivation for the strategic application of the IS approach was essentially economic through the creation of "profit centers" that utilized byproducts of upstream plants [297]. Environmental concerns apparently emerged in the 1990's when the industry sought to improve both product quality and environmental performance, getting the ISO9001 certification in 1998 [297].

Evolutionary path Its transformation from a stand-alone refinery to an industrial symbiosis-based biorefinery was a five-decade process carried out to cope with governmemnt policies aimed at the sustainable development for the sugar industry. The policies advocated profit sharing between farmers and manufacturers, increased product quality, and greater environmental protection [297]. The first strategy was then to set up new businesses to utilize byproducts of upstream plants [297].

With a processing capacity of 1 million tonnes of sugarcane per year, GG's symbiosis enabled the creation of two product chains (or core businesses): the sugar chain (sugar and ethanol plants) and the paper chain (pulp and paper mills). In the former, cement and compound fertilizer are also produced, while the paper chain uses sugarcane bagasse as input (without the pith) and recycles black and white liquors for alkali, fiber and water recovery (Figure 3.2).

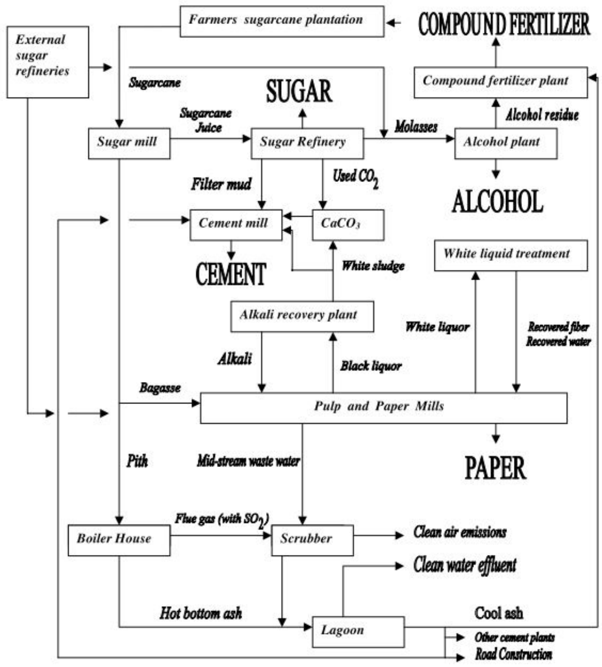

Figure 3.2: Industrial symbiosis of Guitang Group (China). Source: [297].

Outcomes In terms of outcomes, GG raised its income by 10% from improved sugar quality. Also, sensible reduction on input acquisition and waste disposal was obtained. For instance, 80% of the alkaly was returned to the process after recovery, costing less than half of the price of the virgin material.

Such strategies also had positive spillovers to the surroundings. Besides the reduction of pollution levels, local labor market was highly affected by GG's initiaves. Qualified workers refrained from leaving the province to more developed areas. Also, improvement of educational standards was also attained with the support to research institutes: Sugar Refinery Institute, Paper Institute, Environmental Protection Institute, Biotechnical Institute, and Automation Institute [297]. Indeed, just like with the Bazanzourt-Pomacle biorefinery, investment on research and development (R&D) was crucial to the results achieved, which, in 2001, made GG's site an official eco-industrial demonstraton park in China.

British Sugar refinery (UK)

British Sugar's Wissington site is also a case not self-designated biorefinery but that can be understood as such. It consumes sugar beet to produce a large variety of products (sugar, ethanol, betaine, tomato, etc.). The consistent application of industrial ecology principles, particularly the industrial symbiosis approach, granted such diversification.

Operating since 1925, the referred facility was acquired by British Sugar in 1930, which was later bought by the Associated British Foods (ABF) in 1991. Industrial ecology became part of the company strategy since then. At this time, ABF sought a solid model to maintain economic stability and sustainability in a context of increasing volatility of sugar prices and progressive withdrawal of protectionist measures in the European Union.

Exogenous context Part of the exogenous factors around the development of British Sugar Wissington's site coincides with that of the Bazancourt-Pomacle biorefinery on what concerns to the GATT/WTO agreements and the CAP reforms. It is also similar to Guitang Group's in terms of the relationship with feestock suppliers. The reduction of protectionist measures that followed the CAP reforms, demanded Britsh Sugar to watch and maintain the competitiveness of beet root farming, and discourage them to shift to alternative, potentially more lucrative or less-risky crops [246].

Another inffluence factor was the expansion of the availability of cheap sugar from sugarcane crops in least developed economies. The strategy was then to working with the farmers to constantly improve crop yields. Besides a close working relationships with the local agricultural community, British Sugar provided direct investment in research and development (R&D).

Endogenous context British Sugar was also a state-owned company operating in a very protected environment (with production subsidies and quotas). Its acquisition by AB Sugar in 1991 together with the gradual withdrawal of governmental support, changed its market strategy towards continuous improvement and growth, which was carried out through the valorization of residual streams. This valorization occurred first internally with the creation of new businesses and later on with joint ventures and external companies making use of non-explored byproducts.

Evolutionary path As a result, the sugar system was gradually expanded to an integrated biorefinery. The first move was to press, dry and pelletize the residual pulp and commercialize it as animal feed. Then, the CO_2-rich flue gas and heat from the cogeneration unit was used to cultivate tomato, while betaine and raffinate were extracted from the resin separation unit to be sold to cosmetic and animal feed manufacture respectively. Thereafter, a bioethanol plant was installed of which residual vinasse was also commercialized as animal feed. The last (up to 2014) expansions were a CO_2 recovery unit and a joint venture for ethanol production (Figure 3.3).

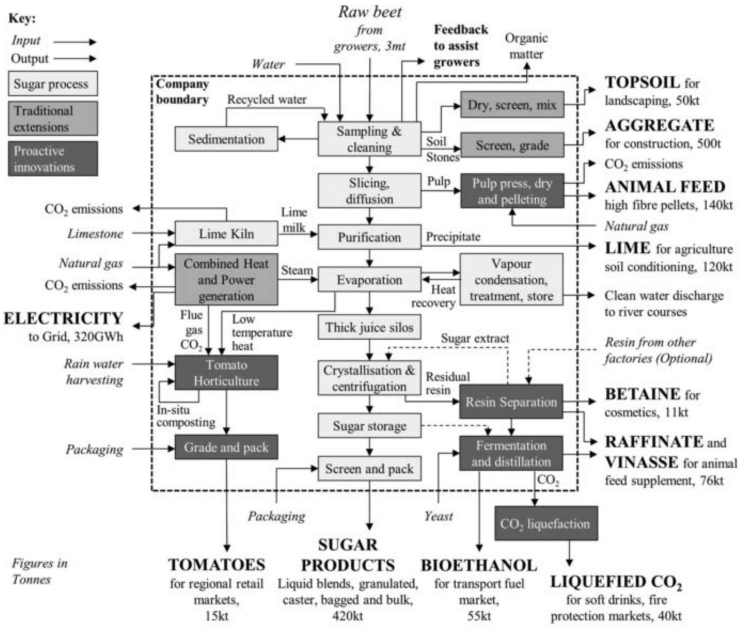

Figure 3.3: Industrial symbiosis of British Sugar (UK). Source: [246].

Outcomes These business inovations allowed the company to remain competitive in the sugar market whereas diversifying the sources of income and growth, and increasing revenues in 30% in 2012. Benefits reported to the site outskirts include 25% reduction of waste to landfill in 50% and reduction of local pollution from agrochemicals due to topsoil recycling and R&D efforts in the British Beet Research Organization (BBRO) — established to ensure competitive and reliable supply of raw sugar beet. Figure 3.4 shows the chronology of the business innovations of each case covered.

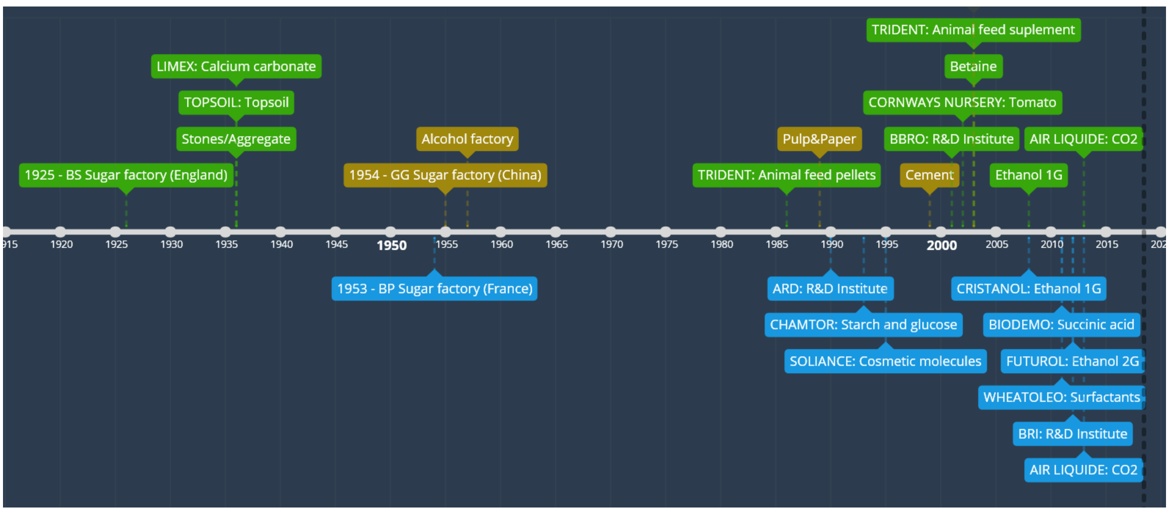

Figure 3.4: Chronology of each empirical case of IS-based biorefinery. (BS: British Sugar (green); BP: Bazancourt-Pomacle (blue); GG: Guitang Group (light brown)) Source: created by the author from [241, 246, 297].

3.4 Framework for the emergence of industrial symbiosis-based biorefineries: a 3-stage process

An industrial symbiosis-based biorefinery is a biorefinery established from the gradual implementation of the industrial symbiosis approach in a conventional agro-industrial facility. A conventional agro-industrial facility is, in turn, a site that produces agro-industrial commodities using mature (or conventional) technologies.

The empirical cases described concern unrelated studies from distinct economies performed in different periods, with distinct methodologies and purposes. However, a common pattern for the consolidation of the industrial symbiosis-based biorefinery could be identified:

1. they all started from a single-product facility from now on referred as *core business*

2. this facility then started to perform internal symbiosis through the internal recycling of material streams to increase the resource efficiency of its core business (*primary internal symbiosis*)

3. the internal symbiosis then expanded to peripheral businesses through investment on new businesses or facilities to capture value from residual streams not yet recycled and with some affinity with the core competence (*secondary internal symbiosis*)

4. once opportunities were internally explored, the sites started to either accept or prospect external partners to acquire residual streams, either offering the site for the installation of new facilities or transporting the byproducts to be processed in an existing facility outside the biorefinery site (*external symbiosis*)

5. Moreover, the moves were mainly economically motivated although environmental concerns also played a role in their decision-making, and

6. The overal process was unplanned.

In terms of the design of a industrial symbiosis-based biorefinery, patterns 1, 2, 3 and 4 provide a reference of the sequential stages necessary for the biorefinery consolidation. Pattern 5 reinforce the economic dimension as a necessary element for the endeavour to thrive. Pattern 6 is provocative in the sense that it suggests that there must be further common elements that make such unrelated and unplanned initiatives to follow similar paths.

The first common element is the market context. The three biorefineries started as sugar manufacturers. They were then operating in an increasinly volatile market after the GATT rounds departing from 1947 and CAP reforms (in Europe) from 1962 on. This instability came coupled with restrictive environmental regulations in the agro-industrial sector. There was then a pressure to raise competitiveness while reducing environmental burdens in the surveyed reports.

Endogenously, some common characteristcs were also identified. The first was the willlingness to perforfm investments and take calculated risks. Second, active partnership with feedstock producers through research and development and fair remuneration. Third, the major role played by research an development partners and the assignment of an innovation team to prospect opportunities. And finally, the attention to the timing for when to make each move (from inner to outer endeavors).

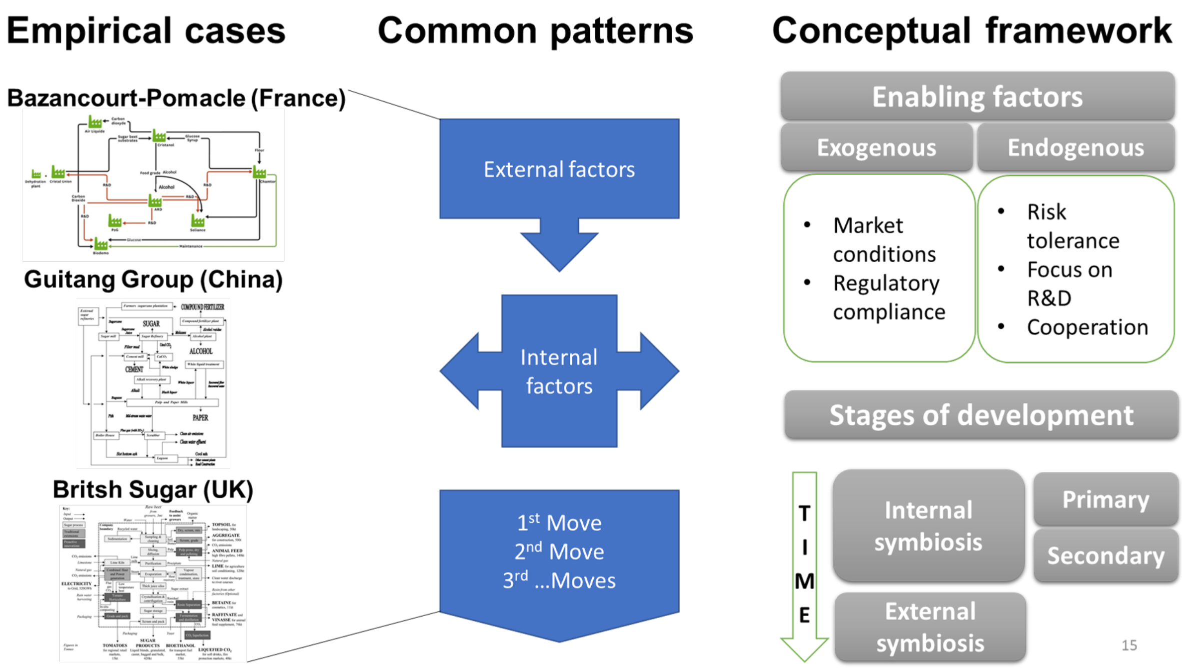

Figure 3.5: Conceptual Framework

Summarizing, in face of the evidences gathered so far, the development of an industrial symbiosis-based biorefinery can be theorized as a process beginning with the very first single-product agro-industrial facility that, motivated by market and regulatory aspects, perform primary internal symbiosis (site efficiency upgrade through recycling byproducts). Once all viable opportunites for internal recycling are gathered, the existing facility then invests on new facilities and/or businesses related to their core competences to make use of uncycled byproducts (secondary internal symbiosis). The final stage is to perform external symbiosis, openning the site to partners that would absorb yet uncycled streams or sending these streams to partners outside the site.

Despite this process is described as marked stages, in reality they intersect, setting periods of transition from one stage to the other. The uncovered process can then be used to explain and plan the transmutation of agro-industrial facilities into IS-based biorefineries. In the next section we examine the Brazilian sugarcane industry under the light of the process uncovered, pointing the factors that might be hampering it from similar developments.

Following the framework just uncovered in this section, Brazilian sugarcane mills can be said to have accomplished the first stages to become a complete industrial symbiosis-based biorefinery, namely primary and secondary internal symbiosis.

Chapter 4

Methodological proposal for planning the development industrial symbiosis-based biorefineries

In the previous chapter the conceptual framework overarching this research was developed using empirical cases of what was defined here as IS-based biorefineries. This framework is the foundation for the methodological approach proposed in the present chapter. Its purpose is to support the transition process of conventional sugarcane mills in Brazil into IS-based biorefineries through the construction of sequential frames in the form of short-, mid- and long-term scenarios.

The methodology departs from the premisse that the conventional agro-industrial facility exists in a particular territory immersed in a local context. Opportunities for synergies are therefore a function of the productive activities carried out in the context. A set of methods and organized steps are used to devise sequential scenarios representing potential configurations for the industrial symbiosis network resulting from byproducts' internal recycling and external exchanges with surrounding firms.

The methodology stems from (1) the conceptual framework on how IS-based biorefineries emerge from conventional agro-industrial facilities (presented in chapter 3) and from (2) the literature on methodological approaches for planning industrial ecosystems in Brazil [132, 181, 278]. Since, in this research, a planned approach has been devised from unplanned and spontaneous processes, some adaptations had to be performed to grant systematicity to the proposed methodology (Figure **??**).

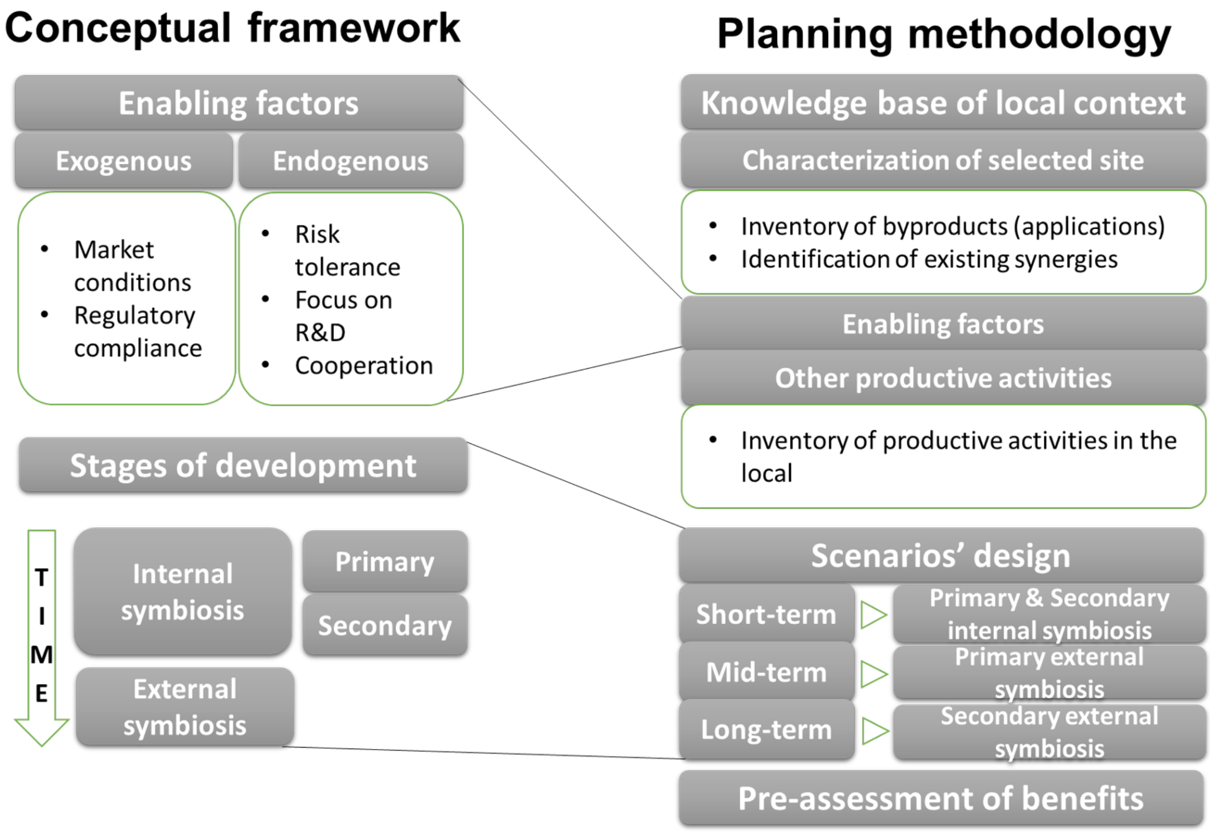

Figure 4.1: Adaptation of the conceptual framework to the planning methodology.

4.1 Knowledge base of the local context

The first step of the methodology is to perform a survey on the location[1]hosting the conventional agro-industrial facility to be assessed. This survey includes the characterization of the facility, the assessment of the enabling factors and the characterization of the productive activities carried out in the local. The information prospected in this stage feeds the scenario assessment.

4.1.1 Characterization of the selected site

The site comprises the *locus* of the conventional agro-industrial facility. The term is used to refer to the area occupied by the units operating in the facility. A facility can then be composed of more than one unit (like a sugarcane mill that usually implies a sugar refinery, an ethanol distillery and a cogeneration unit).

The characterization consists on the technological description of the facility, the

[1]The definition of "local" depends on the scope of the research in terms of the area to be considered for the analysis. In this study, it is is given by the limit of the political-administrative unit (state, municipality, region, etc.) where it is intended to develop the industrial symbiosis network.

identification of input and output streams — especialy the residual streams (refered here as byproducts). The identification of existing synergies (recycling or reuse practices already happening in the site). An inventory is then created consisting of the physico-chemical properties of the byproduct, composition, flow, current destination, and other potential applications each byproduct can have.

4.1.2 Assessment of enabling factors

This stage refers to the assessment of the local context in terms of how it compares with the enabling factors identified in the conceptual framework (chapter 3). It provides a "picture" from the macro (international and national) and micro (human) levels that indicates the likelyhood of implementation of the proposed scenarios. Suggestions of measures other than in the facility or business levels (i.e. in the human or macroeconomic levels) may be proposed from this step.

4.1.3 Other productive activities

Since this methodology predicates the execution of synergies with productive activities operating in the location, an inventory of these firms is required. Besides enabling the development of the mid-term scenario, this inventory also adds to the comprehension of the economic vocation of the local.

4.2 Scenarios' design

As presented in the framework, IS-based biorefineries develop gradually and, preferably, in three sequential stages. This methodology then conceives the design of an IS-based biorefinery as a gradual process conveyed in three successive scenarios: the short-, mid- and long-term scenarios. A reference scenario is also developed as the baseline of the analysis perfomed. It presents the existing agro-industrial site with its units, byproducts and their current destinations, and any existing synergies.

4.2.1 Classification of symbiotic synergies

According to the framework, IS-based biorefineries develop in three stages: primary internal symbiosis, secondary internal symbiosis and external symbiosis (which designates either synergies with existing firms or synergies with new firms). In this methodology, however, its considered that opportunities for waste exchange with existing firms are explored before those with new firms. Then the external symbiosis is split into primary external symbiosis and secondary external symbiosis respectively. The symbiotic synergies considered in this methodology are formally defined below.

- **Primary internal symbiosis** is the synergy perfomed between the processes of the existing system. That is, a byproduct is internally recycled in the industrial processes. It also encompasses exchanges with to the biomass producer or supplier.

- **Secondary internal symbiosis** is the synergy with new facilities and processes pertaining to the same company of the original system. They are related to investments performed by the site owner to create new and more valuable destination to its byproducts.

- **Primary external symbiosis** is the exchange with existing companies located in the surroundings of the agro-industrial site. It comprises the classical notion of industrial symbiosis, "*in which at least two otherwise unrelated species exchange materials, energy, or information*" [59]. Finally,

- **Secondary external symbiosis** is a category developed in the context of the present methodology to differentiate the synergies between the agro-industry and companies already operating in the surroundings from the synergies with new companies — that might eventually be installed in the site or in the surroundings making use of uncycled byproducts. Secondary external symbiosis is the type of move proposed in the long-term scenario.

In the short-term scenario, primary and secondary internal synergies are proposed to the existing system as shown in Table 4.1, while the mid-term scenario covers the theoretical potential for the byproduct streams to become inputs for industries already operating in the location. Therefore, it explores opportunities for primary external symbiosis. The long-term scenario, in turn, explores opportunities for secondary external symbiosis. New productive activities are suggested in the long term to make use of the byproducts that remained uncycled.

Table 4.1: Type of symbiosis in each scenario.

Industrial symbiosis tenants	Scenarios			
	Reference	Short-term	Mid-term	Long-term
Agro-industry	Current configuration	PIS[a]& SIS[b]	PIS & SIS	PIS & SIS
Local industries			PES[c]	PES
New industries				SES[d]

[a] PIS: Primary internal symbiosis.
[b] SIS: Secondary internal symbiosis.
[c] PES: Primary external symbiosis.
[d] SES: Secondary external symbiosis.

4.2.2 Reference scenario

The reference scenario is key for the development of the other scenarios. The level of detail and accuracy of the information gathered in this phase determines the broadness and representativeness of perspectives to be obtained. The characterization of the conventional agro-industrial facility site, the inventory of byproducts, the inventory of synergies and the inventory of productive activities in the surroundings are the inputs required.

Synergy matrix

The synergy matrix (SM) is a design and management tool for the development of industrial symbiosis networks. It consists of a table (Figure 4.2) where the byproducts and their respective producers and receivers are organized in a matrix to indicate the status and opportunities of waste exchange [118, 181]. It was conceived to enable the prompt understanding of the symbiotic network in the reconfiguration of an industrial district into an eco-industrial park [181].

In this methodology, it was adapted to incorporate the scenarios developed, which suggests that it is also capable of reproducing the temporal dynamics of the ISN's composition. And it supports the design of each scenario because it show the waste streams to be recycled.

Scenarios			Firms	Waste stream		
				W_1	W_2	W_3
S_3	S_2	S_1	F_1	G		R
			F_2	R	G	
			F_3		R	G

where:
S_1 is the first scenario: F_1 generates W_1.
S_2 is the second scenario: F1 generates W1, F2 generates W2, and F2 receives W1.
S_3 is the third scenario: F1 generates W1, F2 generates W2, F3 generates W3, F2 receives W1, F3 receives W2 and F1 receives W3.

Figure 4.2: A simplified synergy matrix adapted for IS design through scenarios.

The synergy matrix for design is the main product from the reference scenario to build the short-term's, which is covered in the next section.

4.2.3 Short-term scenario

The short-term scenario comprises the internal reuse or recycling of the byproducts, which can be either on the existing processes or on new facilities. These new facilities would still be related to the core competences of the conventional agro-industrial facility assessed. The purpose of such new facility is to profit more from the feedstock by giving valuable destinations to the byproducts and, thereof, diversifying its markets. New destinations to already recycled byproducts can also be proposed to enable the biorefinery deployment. The inventory of byproducts in the short-term enables proposing the mid-term scenario.

4.2.4 Mid-term scenario

In the mid-term scenario, the biorefinery starts to interact with the surrounding industries through the exchange of waste. In the case of the Guitang Group, for instance, it refers to the sale of filter mud and calcium carbonate to the cement mill nearby.

4.2.5 Long-term scenario

The long term scenario proposes the continuation of the expansion of the symbiotic network through the installation of new productive activities, in the site or in its surroundings to consume uncycled byproducts. It is the case of the liquefied CO_2 facilities in the Bazancourt-Pomacle and British Sugar sites.

Again, in the real world these scenarios are likely to superpose instead of having well defined start and end. Figure 4.3 represents the procedure for the scenarios' development. It can be executed iteratively since for each additional facility in the symbiotic network, a new set of residual streams is likely to be generated causing ever-greater complexity in the analysis. In this thesis, however, the symbiotic networks to be developed focus solely on the residues from the agro-industrial site.

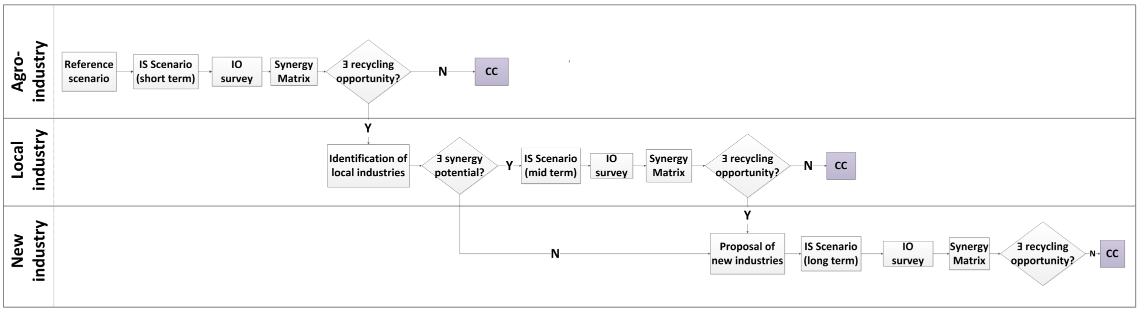

Figure 4.3: Procedure undertaken for agro-industrial symbiosis network.(IO survey: survey of material streams; Backwards E: Existing; CC: closed cycle)

4.3 Pre-assessment of potential benefits

The main differential between the modern and the traditional bioeconomy is the relevance of the social and environmental dimensions. Hence, the methodology also proposes the estimation of the potential benefits of the scenarios conceived. The estimation proposed, however, should be regarded a first-proxy quantifications of the outcomes expected from the IS-based biorefinery development since the pre-assessment of synergies provides an incentive for the materialization of the industrial symbiosis network [262].

The literature on the quantitative assessment of industrial symbiosis network benefits is mainly focused on the physical and financial savings related to the avoidance of waste disposition and virgin resources consumption [58, 113, 273].

Accordingly, in this study we estimate the (1) *feedstock remuneration premium* from the bioplatform chemical production (see section 5), (2) the *direct jobs* (as suggested by Kurup et al. (2005)[171]), the (3) *waste emission reduction* [143, 261] and the (4) *greenhouse gases (GHG) savings* [184]. Together they comprise economic, social and environmental indicators whose values resonate differently in the distinct scenarios.

4.3.1 Feedstock remuneration premium

The computation of the economic indicator also depends on each case, since it is a function of the products and technologies considered. In this study, the feedstock remuneration premium is estimated. It consists on the potential premium (or agio) over the sugarcane bagasse remuneration as a result of its use for succinic acid production in comparison to its use for bioelectricity [2]production. This metric is especially relevant in the present context where the bagasse is on the verge of being accounted in the sugarcane pricing procedure [4]. So that the more valuable its use, the higher the sugarcane price is likely to become – which is key for retaining the attractiveness of sugarcane farming.

The equation to compute the feedstock remuneration premium is

$$FRP = FR_i - FR_j \tag{4.1}$$

where FRP is the feedstock remuneration premium [3], and FR_i and FR_j are the feedstock remuneration expected from the production of product i (succinic acid) and j (bioelectricity) respectively. FR_i is computed with $FR_i = f_i * P_i * y_i$, where f_i is the fraction of the selling price of product i that corresponds to the feedstock; P_i is the selling price of the product i and y_i is the yield of product i per tonne of feedstock.

[2]Biolectricity is the product conventionally obtained from sugarcane bagasse. In this study we compare the production of succinic acid in the proposed biorefinery with the production of bioelectricity in a biorefinery using biomass integrated gasification combined cycle (B-IGCC). See: Santos et al., (2016) [237].

[3]If $FRP = 0$, it means that both feedstock uses are equivalent in terms of remuneration. If

4.3.2 Direct jobs creation

The estimation of job creation depends on the case and on the information available. In this thesis, it is estimated for the case study using the United States' National Renewable Energy Laboratory approach [150] where job positions of biorefineries are a function of their feedstock processing capacity. Here, the number of managerial positions is kept fixed and equal to the NREL's while new values are computed for operational positions using the equations

$$njobs = \sum_{x} njob_{x,new} \text{ , where} \tag{4.2}$$

$$njob_{x,new} = njob_{x,ref} \text{ , if the job position is managerial,} \tag{4.3}$$

$$njob_{x,new} = njob_{x,ref} * \frac{Pc_{new}}{Pc_{ref}}, \text{ if } (njob_{x,ref} * \frac{Pc_{new}}{Pc_{ref}}) > njob_{x,min} \text{ , or} \tag{4.4}$$

$$njob_{x,new} = njob_{x,min} \text{ , if } (njob_{x,ref} * \frac{Pc_{new}}{Pc_{ref}}) < njob_{x,min} \tag{4.5}$$

$njobs$ is the total number of jobs in the facility, $njob_{x,new}$ is the number of job positions of type x [4], $njob_{x,ref}$ is the reference quantity of job positions of type x and $njob_{x,min}$ is the minimum quantity of job positions of type x. Pc_{new} is the feedstock processing capacity of the biorefinery and Pc_{ref} is the reference feedstock processing capacity.

4.3.3 Waste emission reduction

The waste emission reduction corresponds to the total solid waste and effluents from the mill and biorefinery of which the discharge to the environment is avoided in the short to long-term scenarios. It is estimated by the equation

$$WER_k = \sum_{j} W_{kj} \tag{4.6}$$

adapted from Dong et al (2013) [113], where WER_k is the environmental benefit by waste emission reduction in the scenario k. W_{jk} is the quantity of waste j recycled in the scenario k.

4.3.4 Greenhouse gases (GHG) savings

The greenhouse gases (GHG) savings correspond to the avoidance of CO_2 emissions through the synergies proposed and its computation is analogue to the waste

$FRP < 0$, it means that instead of a premium, the new product is likely to reduce the feedstock remuneration.

[4] $'x'$ corresponds to the type of job position, for instance: plant engineer, lab technician, etc. See section 5.5.3 for the complete list of the job positions, their classification as managerial or operational and reference data.

emission reduction.

Once the methodological path has been explained, the next Chapter presents the case study developed for the Norte Fluminense region of the Rio de Janeiro state.

Chapter 5

Case Study: Industrial symbiosis-based biorefinery in the Norte Fluminense region

This chapter presents the application of the proposed methodology in the case of the sugarcane industry of the Norte Fluminense region of Rio de Janeiro state, Brazil. It starts with the broader motivation for this case study. Then the socioeconomic and environmental contexts of the region are presented, going more in detail in the historical background of the sugarcane industry to identify the enabling factors for the proposed transition. In the sequence, input data, further assumptions and computations considered are described to finally present the scenarios developed and the pre-assessed benefits.

5.1 Motivation for the case study

Brazil figures among the main producers of agro-commodities worldwide. The agro-industry is responsible for 20% of the Brazilian GDP [49] and the sugarcane sector play a major role in it.

The Brazilian sugarcane industry is responsible for 39% and 28% of the sugar and the ethanol respectively being transacted in the world. It is active in 24 of Brazil's 27 states [267]. Five of them concentrate 88% of the national sugar and ethanol production [70] composed of large scale productive units.

Yet, 82 million tonnes of sugarcane per year are still processed into 97 facilities distributed throughout the other 19 Brazilian federations [204, 268]. This amount is greater then Pakistan's, the fifth producer in the world with 63,800 million metric tonnes per year [285]. The sugar production of these "least productive" states is comparable to Guatemala's [102, 271], while ethanol production (3,500 million m^3

[70]) is greater than Canada's, the fifth country in the world ranking [68, 229]. This thesis draws attention to these least productive states, arguing that despite their lower relevance in the national scenario, they are still fundamental for the local contexts, with production comparable to countries in the market.

Brazilian sugarcane industry is often categorized into Center-South and North-Northeast based on the geography and yield levels. However, keeping investigation in this level has been not enough for grasping how each productive area might be affected by national policies and other endeavors. This study then broadens the usual resolution of sugarcane industry research going from the national and macro-regional levels to the meso-regional and local levels.

The case of the Rio de Janeiro State is emblematic. Its northern region, referred here as Norte Fluminense, was once the major sugar producer in the country but has lost this position to become Brazil's main oil & gas (O&G) producer (offshore fields), currently responding to 68% of national O&G production [12] and figuring among the least productive areas in the sugarcane industry nationwide. Still, the huge O&G revenues has merely been invested on initiatives to compensate the O&G market volatility and its potential unavailability in the future [202, 218], creating a context of dependency and vulnerability [205].

5.2 Local context

Norte Fluminense is the largest region of Rio de Janeiro state in terms of area (Figure 5.1), with 9,750 km^2 of extension, 9 municipalities and 849,515 inhabitants [151]. It was once the major sugar producer in the country but lost this position before becoming Brazil's main (O&G) producer in the past four decades, due to the offshore hydrocarbon discoveries in the 1970's.

Figure 5.1: Norte Fluminense region. [20].

Its sugarcane industry only supplies 6% of the state's ethanol demand [266, 267, 269]. Nevertheless, it is still the main producer of sugarcane in Rio de Janeiro [52, 205], while the revenue of US$ 26 billion per year from the O&G industry [51, 243], 2015) has not been invested on initiatives to offset the deleterious effects of its cyclical downturns [202, 218].

Currently, there are 3 sugarcane mills and one distillery in the region, however only one mill operates continuously (Table 5.1). It processes almost 1 million tonnes of sugarcane per season supplied by 5000 farmers [248] (80% are small produces with up to 300 tonnes of sugarcane produced annually [77]). Crystal grade sugar and hydrous ethanol are the products, attending exclusively the local/regional food and fuel markets respectively. The sugarcane bagasse is burnt for self-supply of power and heat but, unlike modern facilities in the country, there is no production of surplus electricity from bagasse in the Norte Fluminense region. There is also no production of anhydrous ethanol.

Table 5.1: Sugarcane mills in operation in the Norte Fluminense region

Mill	Processing capacity (10^3 t/y)	Main product	Capacity factor (%)
Canabrava	1,500	Ethanol	50 (unstable)
COAGRO[a]	2,000	Sugar and ethanol	67
Paraíso	1,000	Sugar and ethanol	60 (unstable)

[a] COAGRO: Cooperativa Agroindustrial do Estado do Rio de Janeiro.

Actually, the local biofuel production cannot even supply the regional demand, making the region dependent on the imports of ethanol from the State of São Paulo. The availability of feedstock is a major issue. The area allocated to sugarcane crops is 34,300 ha [69], contrasting with 185,000 ha in 1990 [235]. Recently, the state government committed to buy the farmers' production to guarantee their return on investment [10], but the issues of lack of investment in research and new technologies, and the concentration of production factors (mainly workforce and capital) in O&G-related activities still remains to be addressed [76, 218].

O&G is responsible for 60% of its GDP [51] and its royalties comprise 46% of the public revenues [243]. Other industrial sectors such as foods, chemicals, and pharmaceuticals coexist with O&G undertakings. However, even this limited diversity has declined in recent years [130] and the taxes collected from the economic activities cover only 14% of the operating expenses of the public administration [243]. Hence, a fragile socioeconomic situation exists in terms of long-term development since the region is now dependent on a non-renewable resource and on a volatile market [264].

5.3 The selected site and advanced biorefining technology

5.3.1 Selected site: COAGRO

Cooperativa Agroindustrial do Estado de Rio de Janeiro Ltda (COAGRO) was created from the union of 57 sugarcane farmers, who were concerned about the shutdown of many sugar mills in the region, with increasing labor evasion and with the reduction in sugarcane production. Through the Fluminense Association of Cane Planters (ASFLUCAN), they performed studies to evaluate alternatives for restarting an existing mill in the region and the cooperative model was found to be the best to meet their needs.

Then, with the support from the Fund for the Development of Campos (FUNDECAM), in February 2003, COAGRO took over the operations of sugarcane mill São José and initiated the operations in that same season. At that time, 443,726 tons of sugarcane were processed, resulting in 573 thousand bags (50 kg) of crystal grade sugar and 13 million liters of hydrous ethanol. Currently, it processes approximately 1 million tonnes of sugarcane per year, producing 1.3 million bags sugar and 26.5 million liters of ethanol. Table 5.2 summarizes the operating conditions considered of COAGRO facility based on its capacity.

Table 5.2: Mill operating conditions

Property	Value	Unit
Sugarcane hourly processing capacity	500	t_c/h
Sugarcane daily processing capacity	12000	t_c/d
Bagasse produced (wet) per sugarcane processed	273.6	kg_b/t_c
Bagasse (wet) hourly production	136.8	t_b/h
Operating days per year	180	d/y
Bagasse (wet) reserved for mill startup and filter cake	6.5	t_b/h
Bagasse (wet) hourly consumption of the boiler	130.3	t_b/h
Ethanol produced per sugarcane processed	33.33	L/t_c

t_c: tonne of sugarcane.
t_b: tonne of bagasse.
kg_b: kilogram of bagasse.

From the data presented in 5.2, it is evident the discrepancy of COAGRO (producing 33 liters of ethanol per tonne of cane) and a typical distillery in the South/Southeast region that produces on average 80 liters of ethanol per tone of cane [215].

5.3.2 Selected advanced biorefining technology: Succinic acid production facility

Given the estability of the local commercialization of sugar and the replaceability of bagasse by straw, it is assumed that sugar and ethanol manufacturers are more likely to provide alternative use to the bagasse [223]. Hence, the surplus bagasse from the mill is the feedstock considered for the production of succinic acid. The process consists of a pret-reatment stage using Ammonia Fiber Explosion (AFEX), followed by a centrifugation step to separate lignin solids from the cellulose and pentose-rich aqueous effluent. Lignin is then dried and sent to the cogeneration unit. The aqueous effluent is sent to the saccharification and co-fermentation train. There, cellulose is hydrolyzed to glucose and co-fermented with pentose to yield a stream rich on succinic acid. It is then concentrated using electrodialysis and the product recovered through crystallization [244]. Figure 5.2 presents a simplified scheme of the process described.

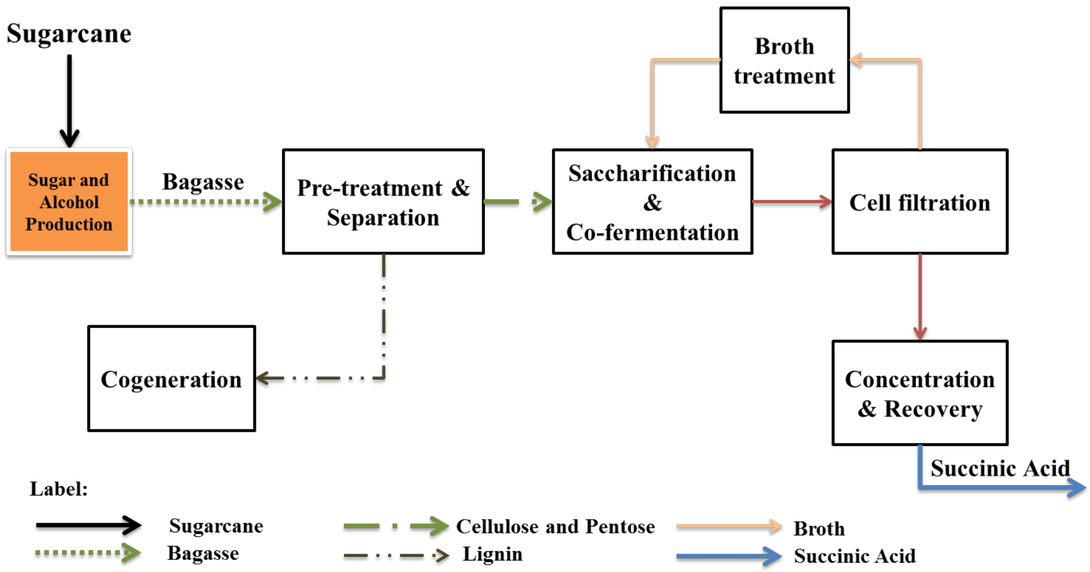

Figure 5.2: Simplified diagram of the Fermentation to Succinic Acid production. Source: Prepared by the author from [244].

5.3.3 The Brazilian market of succinic acid

According the Brazilian Internal Revenue Service, succinic acid is mainly used to the manufacture of reagents and in the food and cosmetic industries as a chemical intermediary to the production of flavoring agents and fragances respectively (Figure 5.3). It is also applied in metallurgy in the treatment of metallic surfaces and on solder paste manufacturing. It is also applied in the pulp and paper industry as internal bonding agent. Less common applications are as bleaching agent for color photographic film and as excipient in the manufacture of medicines [222].

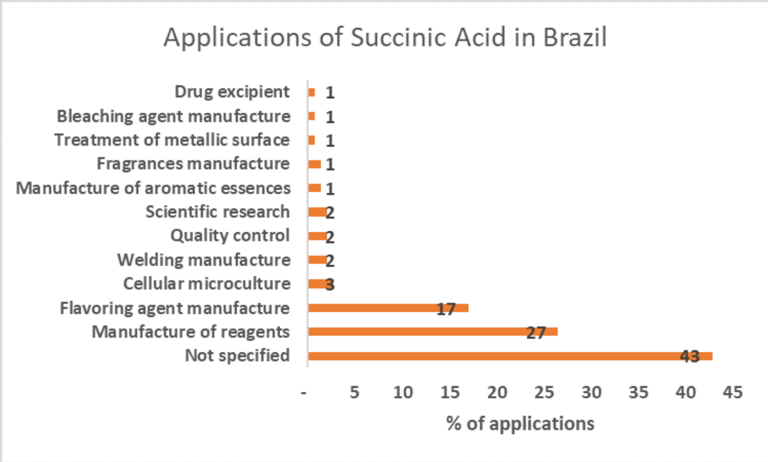

Figure 5.3: Main applications of succinic acid in Brazil from 2014 to 2017. Prepared by the author based on [222].

Currently, there is no production of succinic acid in the Brazilian territory so that all amount consumed is imported, summing US$ 60,000 per year on average in the last four years [222]. When considering the imports of succinic acid derivatives this number grows tenfold to US$ 600,000 thousand dollars per year [222]. In terms of volume, they correspond respectively to 15 tonnes of succinic acid and 170 tonnes of succinic acid derivatives imported per year on average [222].

Itaconic acid, hexadecenylsuccinic anhydride and dimercaptosuccinic acid make up 70% of the imported derivatives in terms of frequency (Figure 5.4), indicating a consistent market for these substances in the country. Hexadecenylsuccinic anhydride is employed in the paper manufacture as internal bonding agent, while dimercaptosuccinic acid is an antidote for heavy metal poisoning [222]. The purity of both substances is reported as 92% and 98% respectively.

Itaconic acid is the methylene succinic acid and the purity of the imported product is reported as 99.5% [222]. While its is application has not been reported, its high purity suggests that it is applied for polymer manufacture, which is normally used in styrene butadiene resins and acrylic latex for textile materials, paper and inks. It improves abrasion and water resistance in materials such as paper, carpeting, textile materials, paints and adhesives [56, 144].

In terms of yearly progress, Figures 5.5 and 5.6 shows that imports of succinic acid tend to increase while that of derivatives is reducing. Despite the difference in terms of order of magnitude of expenditure, in 2017, the imports of succinic acid got close to that of derivatives, which might suggest that succinic acid derivatives' imports are being replaced by internal production.

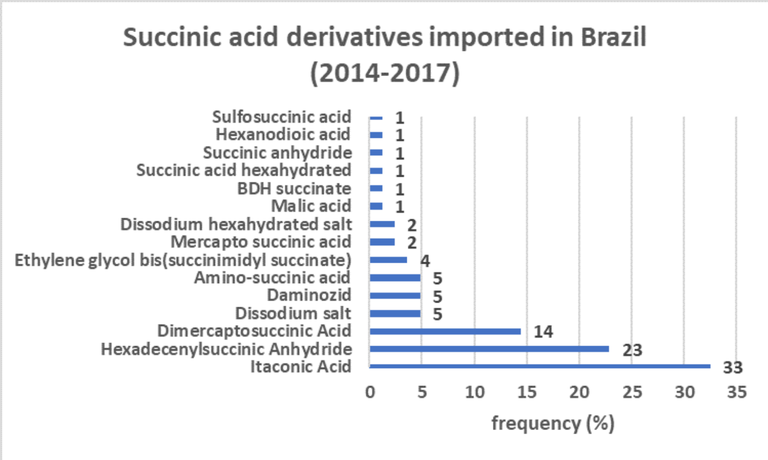

Figure 5.4: Succinic acid derivatives imported Brazil from 2014 to 2017. Prepared by the author based on [222].

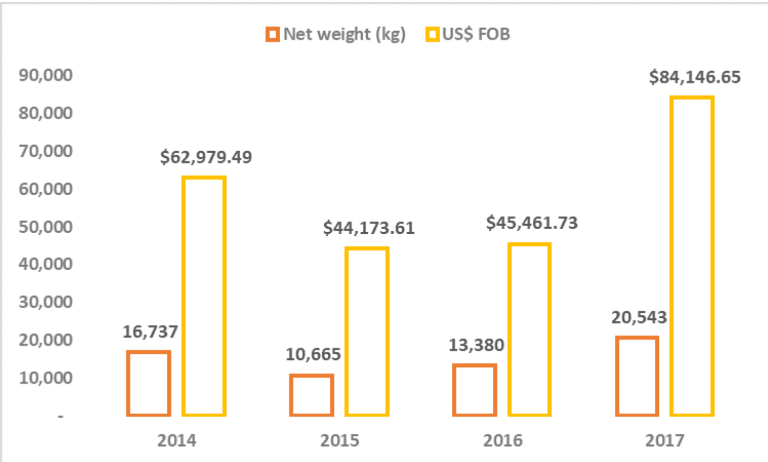

Figure 5.5: Succinic acid imports in Brazil from 2014 to 2017. Prepared by the author based on [222].

5.4 Enabling factors around COAGRO

As it has been seen with the empirical cases from Chapter 3, endogenous and exogenous factors played an important role in the transition of each sugar factory to the consolidated biorefinery comprising enabling factors of the process. This section presents the context around COAGRO to understand the factors that can either support of hamper such transition.

The Appendix A presents a detailed sequence of events centered at Norte Fluminense sugarcane sector since the first years of colonization of Brazilian territory by Portugal. In this section, the discussion covers the period following the first GATT agreements in the 1940's.

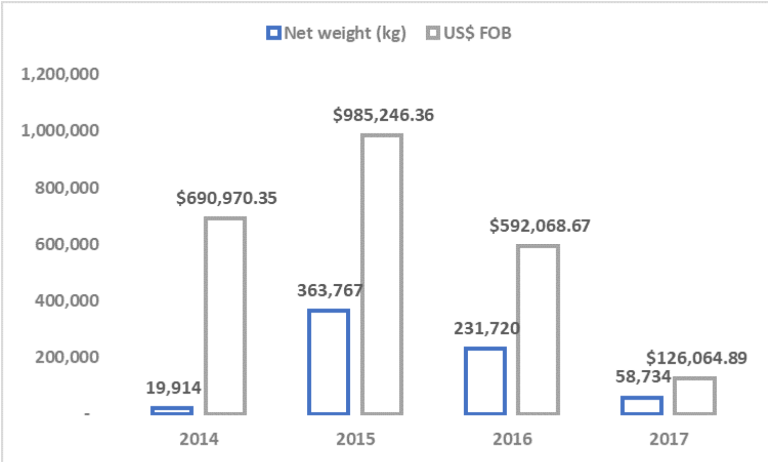

Figure 5.6: Imports of succinic acid derivatives in Brazil from 2014 to 2017. Prepared by the author based on [222].

Exogenous context As the European and Chinese cases, the Brazilian sugar and ethanol production were also affected by the GATT and WTO negotiations that begun in 1947. In that period, the Institute of Sugar and Alcohol (in Portuguese: Instituto do Açúcar e do Álcool or IAA) regulated the Brazilian sugar and ethanol market, establishing production quotas[1], minimum prices of feedstock and also financing operational investments, research and development in the sector.

The petroleum crisis of 1973 motivated the creation of the National Alcohol Program (in Portuguese: Programa Nacional do Álcool or Proalcool) in 1975, providing extra stimuli to Norte Fluminense sugarcane industry. However, in 1974, petroleum reserves were discovered in the coast of Norte Fluminense region (in the Campos basin) permanently changing the economic structure of the region.

The period from 1920 and 1990 was marked by high governmental intervention in the sugarcane sector nationwide accompanied by the creation of financial instruments for the modernization of existing facilities. In the 1990's, coinciding with the Agreement on Agriculture in the GATT meeting of 1994, a deregulation process was carried out in the national sugarcane sector, pushing companies to adapt to the new market structure.

In the Norte Fluminense, the deregulation of the sector, was soon compensated by the financial resources from the royalties paid for the exploration of petroleum in the Campos basin [124, 133, 218]. This monetary stream was used to fund several initiatives in the region also its sugarcane sector [46]. However, other regions in Brazil (like São Paulo and Minas Gerais) had already become great producers,

[1]The quotas were a response to the overproduction that followed the investments performed (mainly in São Paulo) to attend the international market after the 1st World War. Up until that period, beetroot sugar dominated the international market, attending more than 50% of global demand [217].

surpassing the Norte Fluminense capacity by far.

Endogenous context The creation of the IAA in 1933 was followed by a the self-organization process of Norte Fluminense's sugarcane sector to defend its interests [46]. In 1934, the first industrial union (in Portuguese: Sindicato da Industria do Acucar nos Estados do Rio de Janeiro) was created. The farmers bank (in Portuguese: Banco dos Lavradores) was created in 1941, followed by the first co-operative of sugar and ethanol producers and the agricultural union in 1943 and 1945 respectively. By that time, the State of Rio de Janeiro was responsible for 14% of Brazilian sugar production mainly concentrated in the Norte Fluminense region [46].

The 1940's were also a period of massive investments with sugarcane mills upgrading their units to increase production. In 1948, Banco dos Lavradores becomes COOPERCREDI - Cooperativa de Credito dos Lavradores de Cana de Acucar do Estado Rio de Janeiro to improve the access to credits for funding the crops, the Sindicato Agricola de Campos becomes ASFLUCAN - Associacao Fluminense dos Plantadores de Cana, the Hospital dos Plantadores de Cana and the COOPERFLU - Cooperativa Fluminense dos Produtores de Acucar e Alcool were created. COOPERFLU was created to get more loans from the IAA and also for joint commercialization of the sugar produced by the cooperated mills.

However, in the end of the 1950's, Norte Fluminense started to lose market to São Paulo and the Northeast region. Supposedly, it was due to the technological lag of Norte Fluminense mills, inefficient management of productive resources and low crop productivity [46]. In response, COOPERFLU took more loans from the federal government (IAA) and from abroad (World Bank).

Following the launch of the Proalcool, COOPERPLAN, a new cooperative of farmers (in Portuguese: Cooperativa Mista dos Plantadores de Cana) was created in 1976. In 1981, COOPERPLAN bought a distillery, the first modern facility owned by cooperated sugarcane farmers. But the extra funds from Proalcool, were not converted into higher productivity. Operational problems led some mills to require constant monetary withdrawals from COOPERFLU which was discontinued in 1986.

With the deregulation, the mills in the region gradually shutdown going from 21 to 4 facilities in 10 years. Also, sugarcane crops area reduced drastically going from 180,000 ha in the 1990's to around 90,000 ha in 2013 [235]. In this context, COAGRO was created with the funds from petroleum royalties in 2002. It was an effort of 12 sugarcane farmers to keep the sector alive in the region [46, 76]. It started first leasing the mill São José. Later on, MPE Group bought the assets of Sapucaia mill and gave COAGRO the right to operate it [46, 94].

5.5 Input data for the scenarios' design

The data used in this case study were mainly obtained from the literature, institutional reports and interviews with stakeholders (sugarcane mill manager, union representative, local government staff, local researchers, etc.). The following sections detail the acquisition methods for each set of data used.

5.5.1 Processes configurations and material flows

The industrial process data of the sugarcane mill (technological description, inputs and outputs) were obtained from the environmental impact assessment conducted by Rebelato et al. (2013) [221] and further validated during a visit to the mill facilities in May 2015. These are presented in the reference scenario at section 5.6.1.

The technological description of the succinic acid facility is based on the model previously developed by us based on Sharma et al. (2013) [244], consisting of a facility that biochemically converts sugarcane bagasse into succinic acid [237–239]. Its inputs and outputs were obtained from the life cycle assessment performed by Cok et al. (2014) [67].

The symbiotic network developed in this study focuses on the residues from the sugarcane mill and the biorefinery. The quantification is based on the mass balance of the biorefinery model described in Santos et al. (2014, 2016) [237, 238] and the amount of waste released is a function of the units' processing capacity. The parameters used are presented in Table 5.3.

It is important to highlight that the values used for the parameters presented in Table 5.3 are from different sources and not completely representative of COAGRO's facility. In the scope of this thesis, they are used as an initial estimate, so that in future works these numbers should be conciliated. Given that part of the data is from more productive facilities, it is likely that the analysis provided underestimated the residues available for the industrial symbiosis.

5.5.2 Industrial activities

To build the mid-term scenario, an inventory of the productive units of Norte Fluminense was elaborated (Table 5.4). The database of the Rio de Janeiro State Federation of Industries (FIRJAN) was the main source of information. To validate the inventory, interviews with the coordinators of the regional section of FIRJAN and of the Rio de Janeiro State Institute for the Environment (INEA) were also conducted during the field visit.

Table 5.3: Parameters used in the computation of the material flow of the waste streams

Waste stream	Parameter	Value	Unit	Reference
Bagasse	Surplus bagasse produced (wet) per sugarcane processed	134.9[a]	kg_b/t_c	Santos et al. (2014) [Scenario 3] [238]
Straw	Sugarcane straw (wet) per sugarcane processed	92[b]	kg/tc	Dedini (2011) [99]
Filter cake	Filter cake produced per sugarcane processed	20.0[c]	kg/tc	Alcarde (2017) [9]
Vinasse	Vinasse produced per ethanol produced	13.0	m3/m3e	Costa (2009)
CO2	CO2 produced per ethanol produced	759.28	kg/m3e	Xu et al. (2010) [291]
Fusel oil	Fusel oil produced per ethanol produced	0.5	L/m3e	Alcarde (2017) [9]
Used yeast	Dry yeast produced per ethanol produced	25.0[d]	kg/m3e	Alcarde (2017) [9]
Ash	Ash produced per bagasse processed in the CHP unit	23.85[e]	kg/tb	Fiesp/Ciesp (2001) [128]
Lignin	Lignin produced (dried) per bagasse pre-treated	62.65[f]	kg/tb	Rocha et al (2012) [231]
Pentose	Pentose produced per sugarcane processed	10.03	kg/tc	Santos (2013) [239]
Mother liquor	Mother liquor produced per succinic acid produced	1299	kg/tSA	Cok et al. (2014) [Electrodialysis] [67]

[a] $(SurplusBagasseEstimative(t/h) * 1000)/SugarcaneProcessingCapacity(t/h)$ [238].
[b] 0.092 t_{straw}/t_c, which corresponds to 50% of total straw [99].
[c] The author indicates a range from 20 to 40 kg/t_c [9]. The most conservative value was chosen.
[d] 2.5 kg of dried yeast per 100 L of ethanol [9].
[e] 6.2 kg of ash per 260 kg of bagasse in the boilers [128].
[f] From pre-treatment process mass balance where 1194 g of dried lignin was obtained from 95% of 10030 g of bagasse (wet) [231].
kg_b: kilogram of bagasse.
t_c: tonne of sugarcane.
m_e^3: cubic meter of ethanol.
t_b: tonne of bagasse.
t_{SA}: tonne of succinic acid.

5.5.3 Direct job positions

The job positions considered, their classification as managerial or operational and reference data were obtained from a study of the United State's National Renewable Energy Laboratory (NREL) [150]. From, the reference quantities, minimum quantities were established to keep the estimation realistic for a facility operating 24 hours per day with three staff shifts. With the same purpose, in the computation the number of managerial positions is kept fixed and equal to the reference while new values are computed for the operational positions. Table 5.5 shows the reference data and minimum quantity established for each job position.

5.5.4 Products' prices and yields

Minimum selling prices and the succinic acid and electricity yields from the conversion of bagasse are used to compute the feedstock remuneration premium (corresponding to the terms P_i and y_i in equation 4.2). Their values can be seen in Table 5.6. They were obtained from Santos et al. (2016) [237] and Sharma et al. (2013) [244] respectively.

Regarding the fraction of the product selling price that corresponds to the feedstock (term f_i in equation 4.1), the values assumed were 0.52 (52%) for the succinic acid and 0.66 (66%) for the bioelectricity. These values were obtained by Lynd et. al (1999) [179] when assessing feedstock prices as a percentage of product value for different uses of cellulosic biomass [179].

Table 5.4: Inventory of transformation industry[a] from Norte Fluminense region

Types	Number of firms	Types	Number of firms
Machinery	16	Bricks	2
Metallic goods	8	Precast concrete	2
Plastic goods	7	Watercraft	2
Timber goods	6	Signboards	2
Electronic equipment	6	Ice cream	1
Textiles	6	Animal feed	1
Other beverages	4	Condiments	1
Distilled spirits	4	Yeast	1
Canned fruit	3	Bottled water	1
Sugar	3	Industrial gases	1
Metallic structures	3	Lactic acid	1
Candy	2	Household cleaning products	1
Other food products	2	Paints and coatings	1
Vinegar	2	Tire recycling	1
Soft drinks	2	Rubber articles	1
Leather goods	2	Calcium carbonate	1
Paper products	2	Silica	1
Disposable diapers	2	Vessels	1
Industrial soaps and detergents	2	Lighting equipment	1
Drugs	2	Industrial filters	1

Source: [129]
[a] Excluded bakeries, tailoring, industrial services and assembling.

5.5.5 Inventory of byproducts

The potential applications for the byproducts are from scientific literature and technical reports and are presented in the inventory of waste streams (Table 5.7). The inventory also shows the annual material flow considered for each stream of the biorefinery (Table 5.7, second column: "Material flow").

The values were obtained using the parameters presented in Table 5.3 and the operating conditions of Table 5.2 (Section 5.3.1). Hence, the material flow of surplus bagasse is obtained with the following computation:

$$X_b = y_b * X_c \tag{5.1}$$

where X_b is the annual material flow of surplus bagasse from the mill in 10^3t/y; y_b is the surplus bagasse produced (wet) per sugarcane processed (kg_b/t_c, see Table 5.3); and X_c is the amount of sugarcane processed per year in 10^3t/y. X_c is computed through the following expression:

$$X_c = (D_c * dpy)/10^3 \tag{5.2}$$

where D_c is the sugarcane daily processing capacity (t_c/d, see Table 5.2); and dpy are the operating days per year (d/y, see Table 5.2). The computation of annual material flows for straw, filter cake, and pentose are analogous to that of the surplus

Table 5.5: Reference and minimum quantity of job positions for the succinic acid facility and their respective classification^a.

Job positions[b]	**Reference quantity**[b]	**Minimum quantity**	**Classification**
Plant manager	1	1	Managerial
Plant engineer	2	2	Managerial
Maintenance supervisor	1	1	Managerial
Laboratory manager	1	1	Managerial
Shift supervisor	4	3[c]	Operational
Lab technician	2	3[c]	Operational
Maintenance technician	12	3[c]	Operational
Shift operators	20	6[d]	Operational
Yard employees	4	1	Operational
Clerks and secretaries	3	1	Operational
Lab tech-enzyme	2	3[c]	Operational
Shift oper-enzyme	8	3[c]	Operational

[a] The reference feedstock processing capacity is 2,000 dry metric tonne per day [150].
[b] Source: [150]
[c] One per shift.
[d] Two per shift.

Table 5.6: Parameters used to compute the remuneration premium of the sugarcane bagasse

Product	Minimum selling price[a]	Unit	Yield	Unit
Succinic acid	0.57	US$/kg	320.00[b]	kg/tb[c](dry)
Electricity	130.24	US$/MWh	1.04[a]	MWh/tb[c]

[a] Source: [237]
[b] Source: [244]
[c] tb: tonnes of bagasse

bagasse.

The annual flow of vinasse is computed with

$$X_v = l_v * X_e \tag{5.3}$$

where X_v is the annual material flow of vinasse from the mill in $10^3 m^3$/y; l_v is the vinasse produced per ethanol produced (m^3/m_e^3, see Table 5.3); and X_e is the amount of ethanol per year in $10^3 m^3$/y. X_e is computed through the following expression:

$$X_e = (X_c * y_e)/10^6 \tag{5.4}$$

where y_e is the ethanol produced per sugarcane processed (L/t_c, see Table 5.2). The computation of annual material flows for CO_2, fusel oil, and used yeast are analogous to that of the vinasse.

Table 5.7: Inventory of byproduct streams from the biorefining system.

Waste stream	Material flow	Unit	Characteristic	Uses in the short-term	Other potential uses
Surplus bagasse	291.29	10^3t/y	Solid and fibrous fraction (lignocellulose) that remains from conventional milling of sugarcane to produce sugar and first generation ethanol	Biorefinery feedstock and fuel of CHP unit	Fuel for CHP; raw material for biofuels, chemicals and polymers
Straw	199.72	10^3t/y	Solid and fibrous fraction (lignocellulose) that remains from the sugarcane cleaning	Fuel of CHP unit	Fuel for CHP production; raw material for biofuels, chemicals and polymers
Filter cake	43.2	10^3t/y	Solid material retained at the filtration of the decantation sludge from the sugarcane juice's clarification	Fertilizer at sugarcane farm	Soil bioremediation; Biogas production through digestion; wax manufacturing; pyrolytic carbon
Molasses	-	-	Mixture of sucrose, glucose and fructose obtained as a residue from the sugarcane juice processing for sugar production	Raw material of ethanol production	Fertigation
Vinasse	936	$10^3 m^3$/y	Residue (mainly composed of organic matter) from the first distillation for the production of ethanol	Partially used for fertigation at sugarcane farm	Biogas production through digestion
CO2	54.67	10^3t/y	Gas released during molasses fermentation to ethanol	Partially used as electron acceptor in bio-SA fermentation	Soft drink production
Fusel oil	36	m^3/y	Mixture of higher alcohols (e.g. isoamylic) released in the second distillation for the production of ethanol	None	Flavoring agent; perfume fixative
Used lube oil	-	-	Used lube oil from the equipment	Lube oil production outside the region	Lube oil production in the region
Used yeast	1.8	10^3t/y	Part of yeast grown during molasses fermentation	Partially used in yeast treatment/recovery process	Animal feed production
Ash	13.42	10^3t/y	Ash from bagasse combustion mainly composed of silicon dioxide and other oxides	Fertilizer at sugarcane farm	Cement production
Flue gas and particulate matter (PM)	-	-	Gases and particulates released through the CHP unit	–	–
Lignin	18.25	10^3t/y	Natural polymer released in the bagasse pre-treatment mainly composed of aromatic alcohols.	Fuel for CHP production	Fuel for CHP production; fuel additives; adhesives
Pentoses	21.66	10^3t/y	C5 sugars that compose the hemicellulose portion of the bagasse. Also released in the bagasse pre-treatment.	Co-fermented to bio-SA	Biogas production through biodigestion; sweeteners, solvents, fuels and additives synthesis
Bio-SA off-specification	-	-	Bio-SA produced out of polymer grade specification	None	Industrial surfactants production
Off-gases	-	-	Gases from sugar fermentation for bio-SA production	Partially reused in the process	–
Mother liquor	121.08	10^3t/y	Effluent from bio-SA crystallization	–	Biogas production through digestion
Diluted salt effluent	-	-	Effluent from electrodialysis containing sodium salt	–	Effluent treatment

The annual flow of ash is computed with

$$X_a = (s_a * R_b)/10^3 \tag{5.5}$$

where X_a is the annual material flow of ash from the mill in $10^3 t/\text{y}$; s_a is the amount of ash produced per bagasse reused in the CHP unit (kg/t_b, see Table 5.3); and R_b is the amount of bagasse reused in the CHP unit per year in $10^3 t/\text{y}$. R_b is computed through the following expression:

$$R_b = (B_b * dpy * 24)/10^3 \tag{5.6}$$

where B_b is the bagasse hourly consumption of the boiler (t_b/h, see Table 5.2).

The lignin material flow is estimated similarly to the ash's, differing from it in the use of surplus bagasse (X_b, see equation 5.1) and the lignin produced (dried) per bagasse pre-treated (Table 5.3).

The estimation of the annual production of mother liquor is a function of the succinic acid expected production as shown in the equation that follows:

$$X_m = c_m * X_{SA} \tag{5.7}$$

where X_m is the annual material flow of mother liquor from the succinic acid production process in 10^3t/y; c_m is the mother liquor produced per bio-SA produced (kg/t_{SA}, see Table 5.3); and X_{SA} is the annual production expected of succinic acid, which is estimated with:

$$X_{SA} = (X_b * y_{SA})/10^3 \tag{5.8}$$

where y_{SA} is the yield of succinic acid per surplus bagasse pre-treated (kg/t_b, see Table 5.6).

5.5.6 Basis of the pre-assessment

As presented in Section 4.3, four indicators are suggested to evaluate the potential benefits of the scenarios proposed: the waste emission reduction, GHG savings, potential for job creation and feedstock remuneration premium.

In this case study, the waste emission reduction differs in the short, mid and long terms. In the short term, it comprises the straw and dried lignin recycled in the proposed scenario, so that the value considered is the sum of the respective material flows presented in Table 5.7 (equation 5.9).

$$WER_{st} = W_{st,s} + W_{st,l} = X_s + X_l \tag{5.9}$$

where WER_{st} is the waste emission redution in the short-term scenario; $W_{st,s}$ and

$W_{st,l}$ are the quantity of straw and lignin recycled in the short-term scenario respectively; and X_s and X_l are the annual material flow of the straw and the lignin presented in Table 5.7.

The computation is analogous for the other scenarios, additionally considering the fusel oil and used yeast recycled in the mid term, and the mother liquor, biomass and waste sludge (from the succinic acid process) recycled in the long-term scenario.

The GHG savings in the short term correspond to the amount of CO_2 consumed in the succinic acid production. It is computed with

$$W_{st,CO_2} = c_{CO_2} * X_{SA} \tag{5.10}$$

where W_{st,CO_2} is the amount of CO_2 consumed in (or "saved through") the succinic acid production and c_{CO_2} is specific consumption of CO_2 per succinc acid production — considered 289 g of CO_2 per kg of succinic acid [67]. The remaining amount of CO_2 from the ethanol production is considered to be released to the atmosphere.

In the mid and long terms, the remaining amount of CO_2 from the ethanol production (Table 5.7) is added to W_{st,CO_2}, considering that the soft drink producers would buy it.

The potential amount of new jobs positions was estimated solely for the short term. It refers to the positions that would be created with the installation of the succinic acid facility. Using equation 4.2, the estimated quantity of each job position is shown in Table 5.8. As show in equation 4.2, they are further summed up to obtain the value of the indicator.

Table 5.8: Estimated quantity of each job position for the succinic acid facility[a].

Job positions	Estimated quantity
Plant manager	1
Plant engineer	2
Maintenance supervisor	1
Laboratory manager	1
Shift supervisor	3
Lab technician	3
Maintenance technician	3
Shift operators	6
Yard employees	1
Clerks and secretaries	1
Lab tech-enzyme	3
Shift oper-enzyme	3

[a] Reference data used is in Table 5.5.

The parameters to compute the feedstock remuneration premium were explained in Section 5.5.4 and computed using equation 4.1.

5.6 Scenarios for an industrial symbiosis-based advanced biorefinery in the Norte Fluminense region

5.6.1 Reference scenario

The reference scenario comprises the sugarcane farm, the sugar and ethanol production facilities and the combined heat and power generation (CHP) or cogeneration unit 5.7. The farm supplies 1 million tonnes of sugarcane per year to the mill. It then co-produces bagasse, filter cake and molasses in the sugar unit; vinasse, CO_2 and used yeast in the ethanol unit; and ash in the cogeneration unit. Other outputs are used lube oil [2]and the other effluents (condenser effluents from sugar production, phlegm from ethanol production and boiler effluents from the cogeneration unit).

As already stated in section 2.3.3, some material cycling practices became *sine qua non* deeds in the Brazilian sugarcane industry. In the assessed site, as in the majority of mills in the country [203], the bagasse is used as fuel in the cogeneration unit, while the filter cake and the ash from CHP are recycled to the farm as fertilizer. The molasses are raw material to the ethanol production and the vinasse is recycled to the farm for fertigation. The other output streams are discarded. Table 5.9 show the byproducts of the sugarcane mill, the respective facilities producing them, and the existing and potential internal synergies.

Table 5.9: Synergy matrix of the sugarcane mill assessed.[a] (***existing synergies are in bold italics***)

Facilities	Byproducts[b]																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Farms[b]	G	G	G	G		***R***	R					***R***	***R***			G	G
Sugar refinery					G	G	G									G	G
Distillery							***R***	G	G	G	G/***R***	G				G	G
CHP unit			R		***R***								G	G	G	G	G

[a] G: generate; R: receive; G/R: generate and receive.

[b] 1: Culm; 2: Leaves; 3: Straw; 4: Tips; 5: Bagasse; 6: Filter cake; 7: Molasses; 9: CO_2; 10: Fusel oil; 11: Used yeast; 12: Vinasse; 13: Ash; 14: Flue gas; 15: Particulate matter; 16: Other effluents; 17: Lube oil.

[c] In this table, *Farms* refer to the byproducts coming from the farms, which are those obtained from the sugarcane cleaning.

According to the framework and methodology developed, the assessed site performs only internal symbioses. It is worth to reinforce however that these synergies

[2]Lubricating oil

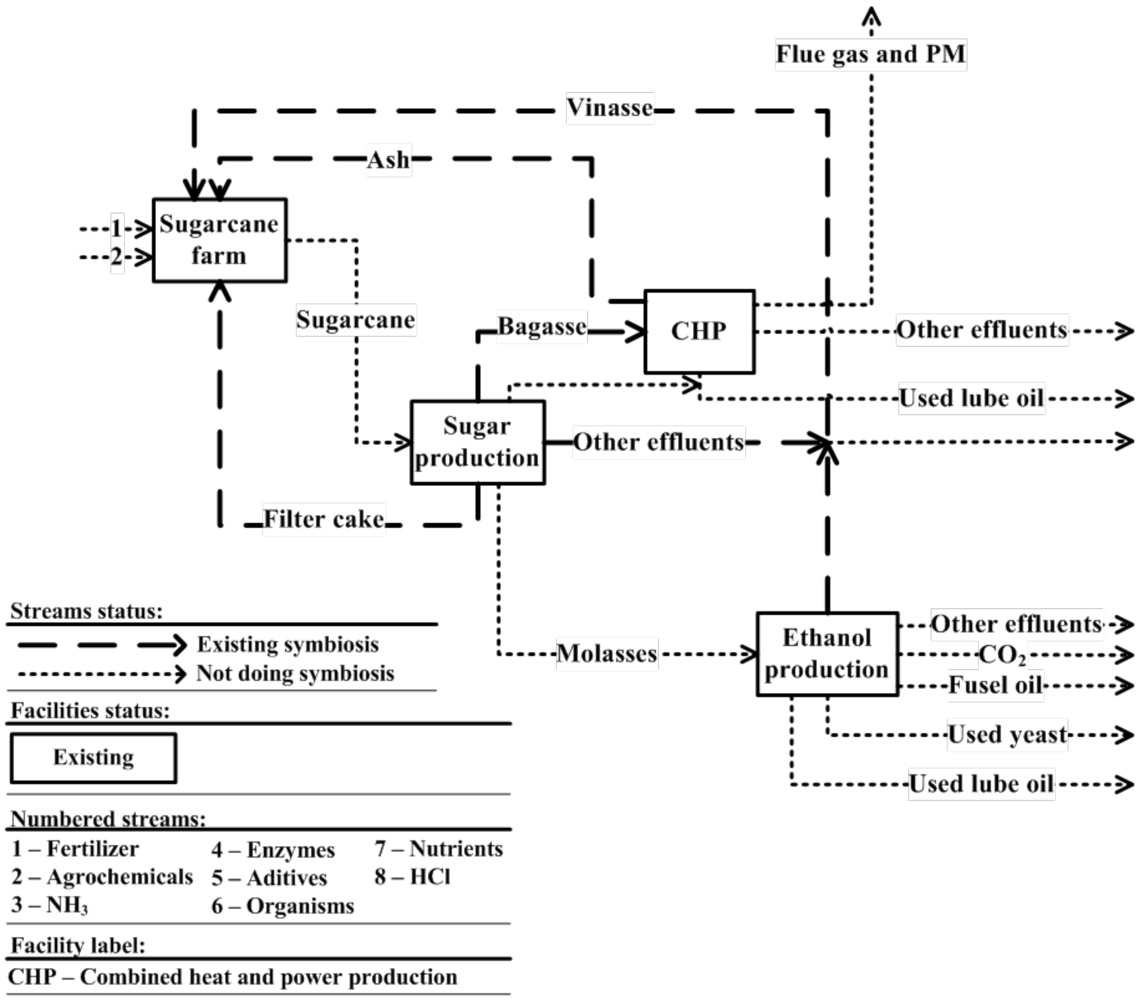

Figure 5.7: Diagram of the reference configuration. Source: Prepared by the author.

Note: The main products (sugar, ethanol, electricity) were omitted on purpose from the figures in order to give emphasys to the byproducts network.

were incorporated in the conventional configuration of sugarcane mills since the beginning of 20th century (reuse of bagasse in the cogeneration) and 1970's (recycling of vinasse and filter cake to sugarcane crops). It is inconceivable to build a new sugarcane mill in Brazil without them.

The reference configuration is also a reference in terms of the productive activities being performed in the region besides the sugarcane industry. In the base year (2013), there were 28 industrial sectors in Norte Fluminense made up of 82 facilities. Table 5.4 lists these sectors and the respective number of firms in the region.

The reference configuration is the starting point for the other scenarios. From 17 byproducts mapped, only 6 are being recycled — which were the most annoying in terms of volume generated and, later on, in terms of polluting potential. But not all amount produced are really recycled (in the case of the vinasse, for example) and also there are other byproducts with higher value applications not being explored (like fusel oil and CO_2). The result is a wide spectrum of possibilities in the design of symbiotic networks.

5.6.2 Short-term scenario

In the short run, the sugarcane bagasse would be diverted from the CHP unit to the succinic acid facility. The new facility would be installed in the short term adjacent to the mill to use bagasse and CO_2 from the existing facility (Figure 5.8).

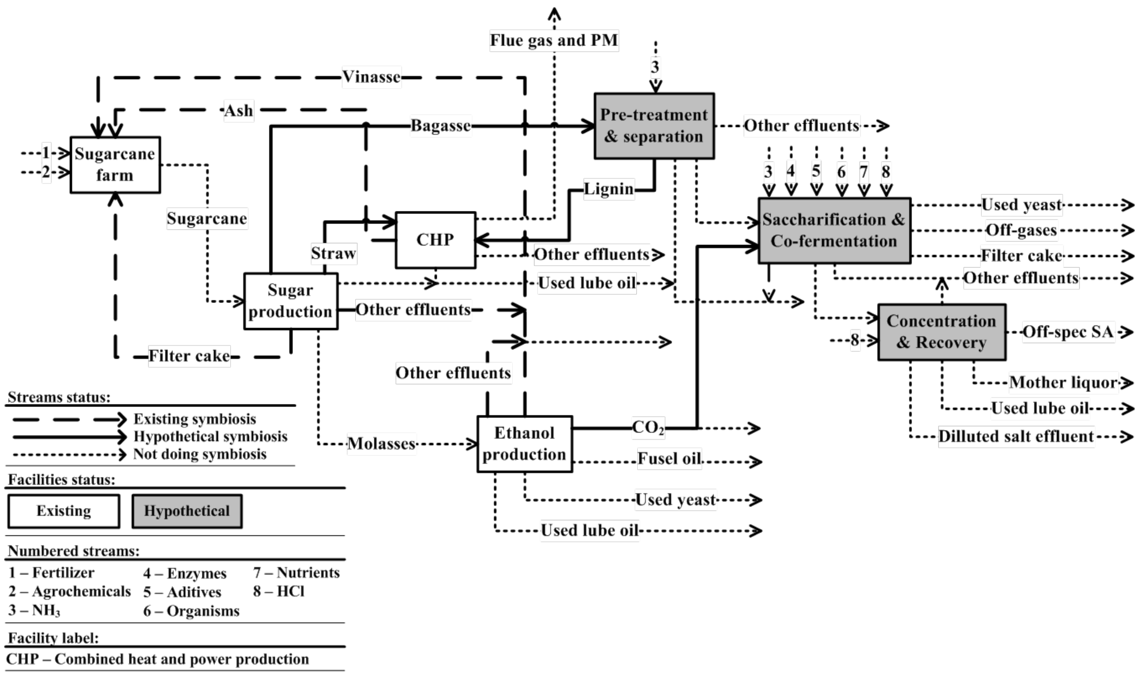

Figure 5.8: [Flowchart representing the short-term scenario. Source: Produced by the author.

However, 90% of the bagasse is currently occupied in the cogeneration unit. This scenario would then demand the upgrade of the cogeneration unit to make more bagasse available for other usages. According to a previous study from the author [236, 239], 50% of the bagasse produced would be available if the cogeneration process was upgraded from the current configuration — low-pressure (21 kgf/cm^2 and 320 ^{o}C) boiler followed by steam turbines, a single stage backpressure turbogenerator and a reduction valve — to a medium pressure boiler (42 kgf/cm^2 and 420 ^{o}C) coupled with condensation/extraction turbogenerators (CD/EXT TG) [238].

Therefore, in the succinic acid scenario, an extra investment would be required in addition to that on the bagasse pre-treatment unit and on the succinic acid fermentation and purification units. Additionally, the straw recovered from sugarcane cleaning and the dry lignin from the pre-treatment process would replace the bagasse as fuels for the cogeneration unit which would require more investments for the adaptation of the furnace burners to the new fuels.

In the short-term scenario, the sugarcane system would expand with the succinic acid facility, adding four more byproducts (lignin, off-gases, mother liquor and diluted salt effluent). Eighteen waste streams would then make up the system. Eight would come from the existing sugarcane mill, six would be from the biorefinery (short-term scenario), and four would come from both. The synergy matrix would then be updated to the one shown in Table 5.10 (from the 3^{rd} column on).

The short-term scenario is then characterized by two new primary internal symbioses (recycling of straw and lignin in the existing cogeneration unit) and a secondary internal symbiosis (reuse of bagasse in the new succinic acid facility). Also, the increment of the bagasse-based succinic acid facility made possible the inclusion of adhesive manufacturer in the synergy matrix as a potential new facility to be deployed in the local.

5.6.3 Mid-term scenario

The mid-term scenario represents the outset of a regional agro-industrial symbiosis in Norte Fluminense with byproduct exchanges crossing the boundaries of the biorefinery site. The information from the short term presented in Table 5.10 shows that, for the mid-term scenario, the biorefinery can sell its byproducts up to 10 different productive activities operating in the region. Considering that current usages are not likely to change in the mid term, its configuration would be the one depicted in Figure 5.9.

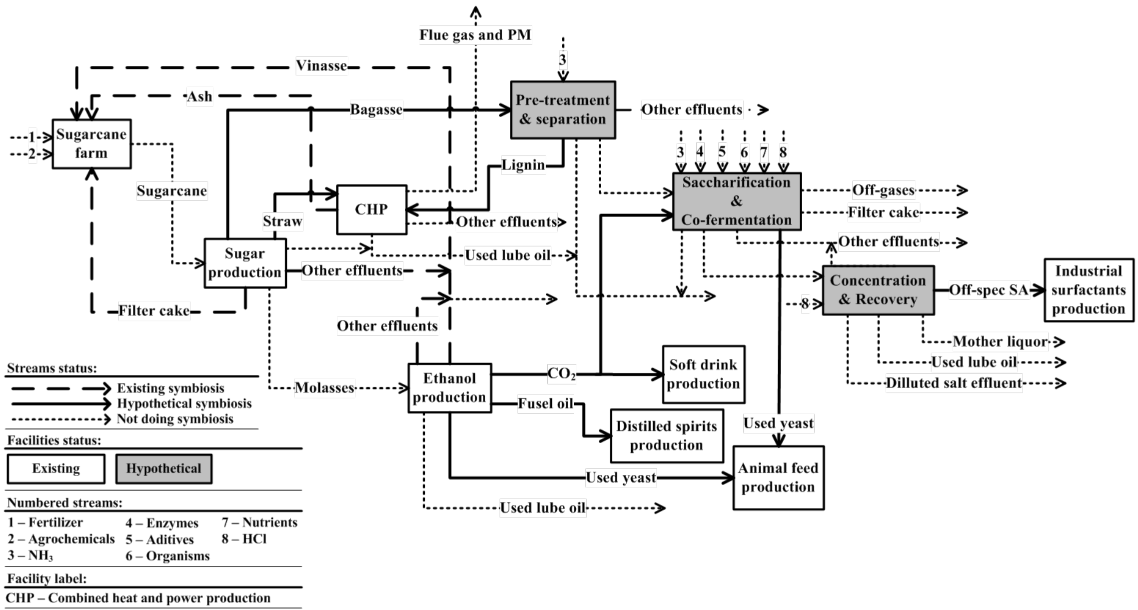

Figure 5.9: Flowchart representing the mid-term scenario.[].

Four out of the 28 sectors listed would provide destination for five waste streams: the soft drinks manufacturer would consume the remaining CO_2; the distilled spirits producer would make use of the fusel oil; the animal feed producer would take the used yeast; and the industrial surfactants manufacturer would take the succinic acid out of specification. The SM for this scenario (second column of Table 5.10), indicates further recycling opportunities to be addressed in the long term.

5.6.4 Long-term scenario

In the long-term scenario (Figure 5.10), a new effluent treatment facility would be in operation to consume the waste streams not addressed in previous scenarios, namely: mother liquor, diluted salt effluents, non-recycled fraction of vinasse and “other effluents”. It would be composed also of a biogas production unit. This biogas would be further sent to the cogeneration unit and part of the lignin would be diverted to an adhesive manufacturer while the filter cake from sugar production would be used as feedstock for wax manufacturing. A lube oil re-refinery would also be deployed to avoid the costs and environmental burdens of recycling lube oil outside the region and would clearly benefit other industries in the region for the same reasons.

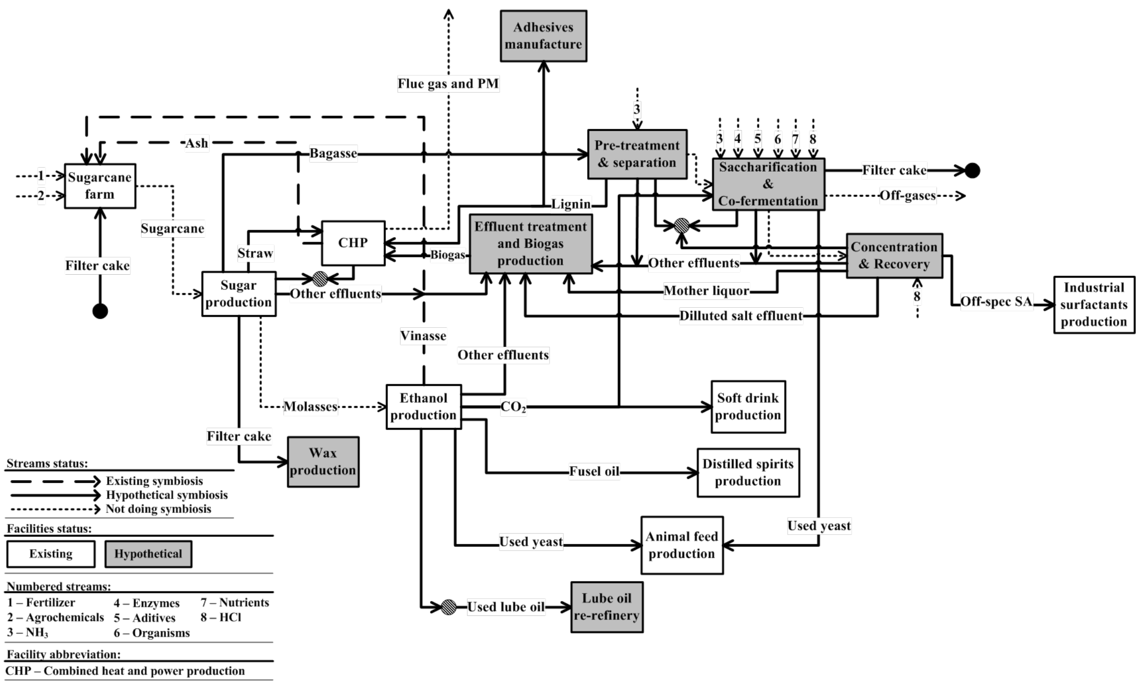

Figure 5.10: Flowchart representing the long-term scenario. Source: Prepared by the author.

Regarding the atmospheric emissions, flue gas and PM would be used for thermal energy recovery before being released, while the off-gases from succinic acid fermentation would be recycled internally to improve the conversion rate. However, the absence of a better description of the off-gas composition hampers the prospects of further uses. Table 5.10 presents the consolidated SM of the agro-ISN proposed.

Table 5.10: Synergy matrix for the scenarios proposed[1]

Scenario	Group	Productive activities	1	2	3	4	5	6	7	8	9	10	11[3]	12	13	14	15	16	17	18
Long-term Scenario / Mid-term scenario / Short-term scenario	Existing system	Sugarcane farm				R	R				R									
		Sugar production	G	G	G	G													G	G
		Ethanol production	R				G	G/R	G	G									G	G
		CHP		R							G	G		R					G	G
	Biorefinery	Pre-treatment & separation			R								G	G					G	G
		Saccharification & Co-fermentation				G		G/R	R									G/R	G	G
		Concentration & Recovery													G	G	G		G	G
Long-term Scenario / Mid-term scenario	Existing firms	Animal feed production						R												
		Soft drinks production							R											
		Distilled spirits production								R										
		Solvents production[3]											R							
		Surfactants production													R					
Long-term Scenario	New firms	Wax production				R														
		Effluent treatment & Biogas production					R									R	R			R
		Adhesives production												R						
		Lube oil re-refining																	R	

Byproducts: columns 1–18.

[1] G: generate; R: receive; G/R: generate and receive.
[2] Waste potentially generated: 1. Molasses; 2. Sugarcane straw; 3. Sugarcane bagasse; 4. Filter cake; 5. Vinasse; 6. Used yeast; 7. CO2; 8. Fusel oil; 9. Ash; 10. Flue gas and PM; 11. Pentose; 12. Lignin; 13. Off-specification bio-SA; 14. Diluted salt effluent; 15. Mother liquor; 16. Off-gases; 17. Used lube oil; 18. Other effluents.
[3] The biorefinery concept considered in this study also converts pentose to bio-SA, so that it is not a residue in this particular case. However, other technological routes considers it a by-product [67, 210, 231].

5.7 Estimation of potential benefits for the region

The potential benefits in the short-term scenario are those related to the implementation of the biorefinery, while those in the subsequent scenarios result from the expansion of the symbiosis outside the sugarcane sector. Table 5.11 shows that the waste emission reduction of the agro-ISN designed can go gradually from 217 thousands (in the short term) to 350 thousand tonnes per year in the long term.

Table 5.11: Potential benefits for each scenario of the agro-ISN proposed.

Benefits	Short-term Scenario	Mid-term Scenario	Long-term Scenario
Waste emission reduction (t/y)	216,971	218,800	283,957
GHG savings (t/y)	26,939	54,668	54,668[b]
Job creation (jobs)	28	—	Jobs from adhesives manufacturer, wax facility and lube oil re-refinery (not estimated)
Feedstock remuneration premium ($/tb)[a]	5.83	5.83[b]	5.83[b]

[a] tb: tonne of bagasse
[b] *Ceteris paribus.* Assuming that market and technical conditions remain the same.

The waste streams accounted were: sugarcane straw and lignin in all scenarios;

fusel oil and used yeast in the mid and long-term scenarios; and, exclusively in the long term, mother liquor, filter cake and waste sludge from the succinic acid production. Sugarcane bagasse, vinasse, ash, filter cake from the sugar production process and washing effluent constitute the existing internal symbiosis and as such they are not considered in the estimated benefits. The GHG savings correspond to the CO_2 emission from the ethanol fermentation that would be avoided by its use in the biorefinery and in the soft drinks production .

The biorefinery would deliver 28 new job positions to the region in the short term and its succinic acid production would bring about additional $5.83 per tonne of sugarcane bagasse in comparison to the prospects for electricity production presented in (Santos et al., 2016). It is important to emphasize, however, that these results are introductory estimates of a pre-assessment. A more detailed analysis presupposes complementation with more fieldwork for primary data collection.

5.8 Understanding the outcomes

The framework and methodology proposed enabled the theoretical design of an industrial symbiosis-based succinic acid biorefinery in the Norte Fluminense region of Rio de Janeiro State. Nearly 350 thousand tonnes of waste and 55 thousand tonnes of CO_2 per year could be avoided. The scenarios developed showed that, considering only the sugarcane system, eight distinct industrial units could become gradually connected to the agro-industry through waste exchange: four from the chemical sector (industrial surfactants, wax and adhesive manufacturers, and lube oil re-refinery); three from the food and beverages sector (soft drinks, distilled spirits and animal feed production units); and one from the public utility sector (effluent treatment/biogas production plant). The sugarcane farm, together with the effluent treatment/biogas production plant, would be the major recyclers, absorbing three and four waste streams respectively.

The production of succinic acid would contribute to increase the competitiveness of the sugarcane sector of Norte Fluminense region, broadening its operation towards higher added-value markets. Table 5.11 shows that $5.83 per tonne would be the remuneration premium expected for the bagasse when comparing its use for succinic acid and electricity. Distinct values for the fraction corresponding to the feedstock in the selling prices can offset this premium. However this initial finding suggests a higher remuneration of the whole sugarcane value chain as higher added value uses are given to the sugarcane bagasse, which could also mean higher wages in the sector.

Still, the 43,200 t/y of filter cake that would normally be used for bioremediation, could also be digested for biogas production or diverted to the production of wax (as shown in the long-term scenario), reviving the local manufacture of cosmetics, which recently disappeared [130]. The same is valid for the lignin and pentose that could be used for energy purposes but were directed to the adhesives and succinic acid production in the scenarios respectively. Also, more jobs would be expected from these new facilities besides the 28 estimated for the biorefinery.

Such a network could contribute to the sustainable development of the region, balancing its economy while also encouraging bio-based innovation for other economic activities that would be attracted to the region. Indeed, the scenarios evidenced that an agro-industrial symbiotic network could be started before the deployment of the advanced biorefinery since three potential synergies were identified between the sugarcane mill (providing CO_2, fusel oil and used yeast) and existing industries in the region (soft drinks, distilled spirits and animal feed manufacturers respectively).

In the short and medium terms, the industrial symbiosis' outcomes are more likely to benefit the private sectors due to potential public incentives and infrastructure development for the network deployment. In longer terms, society as a whole is expected to profit, since besides the creation of jobs and tax revenues, a more robust and collaborative economy could be built, with reduced dependence on the O&G market and with real perspectives for more valuable use of endogenous renewable resources. Moreover, bio-based niches could be developed for the non-transnational firms currently servicing the regional O&G industry, avoiding the bankruptcy or reorganization waves that follow the cyclical downturns of the sector.

Finally, the development of an ISN depends not only on strategic choices in terms of markets to be attended. It also relies on:

- technological aspects such as the readiness of technical solutions for transportation and pre-treatment of the waste streams;
- economic feasibility of such technical solutions, since the use of residual streams is more desirable when it is cheaper than the use of virgin inputs, guaranteeing that competitiveness is increased afterwards;
- organizational aspects like the existence or willingness to build trust and cooperation within and between entities; and
- regulatory aspects, represented by policies capable of pushing the productive sectors towards redesign and recycling. Taxation of landfill use and incineration and the creation of a regulated waste market are some examples of possible policy measures (Costa and Ferrão, 2010).

Chapter 6

Discussion

This section broadens the perspective over the results obtained, exploring potential implications and deepening insights.

6.1 Scenarios overview

6.1.1 Short term

As previously explained in section 2.3.3, the sugarcane mill assessed can be construed as an IS-based biorefinery that is in its earlier stages. As such, in the short-term scenario, the first move proposed was the instalation of a succinic acid facility to consume the sugarcane bagasse that is currently used as fuel in the cogeneration unit. From this move, the sugarcane straw was proposed as cogeneration fuel to replace the bagasse.

Given that only an overviewed quantitative pre-assessment of the scenarios is performed, care was taken to indicate a convincing perspective in terms of energy supply to sustain the increments proposed in the scenarios. Hence, another move foreseen in the short term was the co-burning of lignin in the boiler's furnaces to compensate for the absence of bagasse.

6.1.2 Mid term

In the mid term, the sugarcane system opens up for exchanges with other industries currently operating in the region that could consume its byproducts.

According to the formal definition of industrial symbiosis, only in this moment the facilities involved would be performing "real" symbiosis. Only from the mid term on, material exchanges "between otherwise unrelated firms" [103] are proposed. It is in this scenario then that the location of the industrial facilities become an issue. The distance between the mill and the potential consumer is crucial for the synergy viability.

The main freight transportation mode at Norte Fluminense is the road, which is among the most expensive of the country [**?**]. The region is also served by 90 km of navegable stretch of the Paraíba do Sul River and by 600 km of railroad that connects the North and Northwest regions of the state of Rio de Janeiro. However, the former is only informally used by the neighborhood, while the railroad is on the verge of disassembly [6, 79].

There are plans for the construction of another railroad in the region. It should connect the ports of Açu and Macaé (inside the Norte Fluminense region), but due to political and economic reasons there is no perspective to be built and operational anytime soon. The conclusion is that, despite considering the whole region in the scenarios may amplify the number of potential byproducts' consumers, it may significantly raise the average costs of the network.

A complementation strategy would be to prioritize closer facilities. Also, the scope of the scenarios could be reduced to the municipality level. Another possibility would be to, during the scenario design, to prioritize higher value or higher demand destinations that would compensate for the distance.

6.1.3 Long term

From the mid-term scenario, six byproduct streams remained uncycled the mother liquor and diluted salt effluent from succinic acid concentration and recovery; non-recycled vinasse from ethanol production; "other effluents; used lube oil; flue gas and PM from the cogeneration unit; and off-gases from the succinic acid co-fermentation.

These streams comprises the least valuable byproductss as indicated by the lack of applications other than energy production. Exception is given to the (1) used lube oil that can be treated and used for the same purpose; and (2) the flue gas that can be used in greenhouse crops for its heat and CO_2 content[1]. The off-gases from succinic acid co-fermentation are recycled in the process, but are ultimately released to the atmosphere.

It could be said that this observation keeps coherence with the seminal heuristics of the biorefinery concept that preconizes the exploration of the most valuable streams first, even at the expense of other (less valuable) products [91]. However, it has to be acknowledged that it is more a coincidence than a methodological attribute, since this result is as such because of the composition of the industrial park operating in the region. If there were no industries to consume the most valuable materials in the mid term, this "coherence" would not be observed.

Also in the long term, two byproducts already doing symbiosis in previous scenarios were suggested to change their destinations to more valuable used. These are the lignin from the pre-treatment and the filter cake from the sugar production unit, which were sent to adhesive material and cane wax manufacture respectively.

Indeed, it is very fortunate to have that happened because the changes of byproducts' destinations are a real issue in industrial symbiosis endeavors []. Changes in industrial symbiosis networks not only affect the facility that promotes the change, but also the whole interconnected system. This reinforces the relevance of building scenarios of development of such systems in an attempt to foresee what might happen in the future, avoiding major disturbances to the symbiotic network through planning and awareness. This also indicates how critical it is a robust and effectively operational change management system, all of which culminates on the strategic role of a symbiosis development and management team like the one created in the industrial symbiosis of Kalundborg (Denmark) [163].

6.2 Symbiotic synergies

The number of synergies throughout the scenarios increased consistently. This is something expected since the methodology preconizes an increased number of potential tenants along the scenarios, which greatly increases the potential of synergies. In the short term, only the agro-industrial units are considered, in the mid term, it opens for the productive activities already operating in the region. In the long-term, the sky is the limit since new activities can be proposed for the region to consume the uncycled streams. At this point, the limiting factor is the availability of technologies to make use of the byproducts or the availability of information about the byproduct to make it possible to propose an application, which was indeed the case with the off-gases from the succinic acid facility.

Also, the growth in the number of synergies, despite the consistent increase, does not increase absurdly as it could be expected, not even exponentially. The number of synergies is limited to the number of byproducts to be recycled, so that there is a "cap" for the symbiotic network. However, it can be attributed to the focus of the study on the byproducts from the agro-industrial site assessed. If the byproducts of the other tenants were taken into consideration, a ever growing symbiotic network might have been observed, with each new tenant adding new byproduct streams to be recycled in the system. This is what has been observed in classical long-term industrial symbiosis experiences, like the one in Kalundborg (Denmark) [] and Kwinana (Australia) [].

Comparing to the cases used as references for the framework developed, it can

[1] This application was not considered in this study's scenarios due to its focus on the transformation industry.

be observed that the overal behaviour goes as expected, with a consistent growth throughout time. However, the empirical experiences present some particularities which can be attributed to the spontaneous nature of their processes. The first aspect is the relatively low number of synergies in the first decades of their development, with sparse endeavors throughout time. This can be ascribed to the learning process and also, to the progressive development of a "critical mass" that comes to a point from which the process gains *momentum* and accelerates as it can be seen especially for the Bazancour-Pomacle and Britsh Sugar cases (in Table **??**).

The second particular aspect relates to their relatively low exploration of primary internal symbioses (or simply symbiosis Type 2, as defined by Chertow (2000) [60] and explained in Chapter 2). As process efficiency improvements have been reported, few explicit references to which were the byproducts involved or to the very interventions performed were available. As it can also be attributable to the spontaneous nature of their development, a more realistic hypothesis is that it is due to the relatively lower prominence of internal symbioses in the realm of industrial symbiosis research and practice. Internal processes and interventions are much more straightforward and involves far fewer actors and interests than external symbioses, which is still a challenging endeavor after almost 30 years of investigation and implementation [65].

6.3 Energy prospects

From the scenarios conceived, some explorations of the energy dimension can be performed since, just like current sugarcane mills, it is desirable that the IS-based biorefineries are self-sufficient in energy supply. From the quantity and diversity of materials potentially fueling the system, this expectation is likely to be achieved if further comparative assessments and feasibility analyses can confirm it.

The first point to be discussed is the energy transitions throughout the scenarios in terms of the set of fuels to be consumed in the cogeneration unit. The current configuration, represented in the reference scenario, is fueled with bagasse. The short and mid terms have straw and lignin replacing the bagasse as it is redirected for succinic acid production from the short term on. In the long term, biogas is added to the fuel mix while part of the lignin is sent to adhesive manufacture.

Technically, these energy transitions will demand equipment adaptations to comply with the different fuels and the co-burning prospect might demand technological development to be enabled. Thus, on the economic dimension, these transitions will demand investments to perform the equipment upgrade and to fund technological development research if there are not optimized options in the market.

Another energy perspective, is the modernization of the whole cogeneration unit to raise its efficiency and increase the surplus bagasse availablility for the succinic acid production.

Additionally, since the materials used as fuels can also have other applications, the scenarios developed might demand modeling efforts and opportunity cost assessments to evaluate which arrangement would provide the best option in terms of energy supply (i.e self-sufficiency) and added value (higher margins). Considering the lignin to illustrate the statement, it can be used as fuel but also as input to the manufacture of adhesive materials. What then would be the best option for the system taking into account the other available fuels and their respective use alternatives? And if more biogas could be made available by receiving effluents from other facilities outside the borders of the biorefinery site? These assessments are left for future research developments.

6.4 Industrial symbiosis-based biorefineries: a new concept?

In this study, it was introduced the notion of the *industrial symbiosis-based biorefinery*, which comprises the conventional agro-industrial facility that applies the industrial symbiosis approach to fulfill the integral use of the biomass through the exchange of its byproducts with other productive facilities, performing market diversification and achieving sustainability and resilience.

This notion has been suggested due to the successful experiences of three biorefineries [241, 246, 297] (two uncovered) that, in the early stages of their operation as simple sugar refineries producing one single product from one single feedstock, implemented practices that today are advocated by the industrial symbiosis approach and thrived.

The cognition of the IS-based biorefinery might contribute to both raise awareness about the industrial symbiosis approach and foster the sustainable and locally conscious materialization of biorefinery concepts. That which take into account, prioritize and take advantage of the specificities and opportunities of the local context, especially in terms of byproducts, knowledge, capacity and infrastructure that can be synergistically exchanged.

Chapter 2 made it clear that the biorefinery concept and the industrial symbiosis are strongly interrelated. But little effort has been dispensed to thoroughly comprehend, explain and promote this relationship [241]. This thesis then represents one more step in that direction.

6.5 From disabling to enabling factors

The first point of attention from the case study is that the assessment of enabling factors has shown that even operating under the same market circumstances as of the empirical cases, the policy agenda and actors attitude may have prevented spontaneous developments on the site in the direction of business diversification. Since this condition is common to approximately 70% of existing sugarcane processing sites [] in Brazil, the development of a methodology for the planned development of IS-based biorefineries, like the one proposed in this thesis, is very convenient, not to say needed.

The unsuccessful initiatives for product diversification and the frustrated experiences with technical improvements in the sugarcane facilities in the past may also have enacted demotivating farmers and mill owners on investment endeavors. At the same time, these facts also indicate their need for support on technological awareness and management, especially in a cooperative fashion, since the literature recurrently mentions the historical discention between farmers and mill owners and between sugar and ethanol producers <sources>.

As other agro-industrial cultures gain traction in the region, the sugarcane industry loses space, demanding alternative continuity perspectives. While it is apparently not reasonable to aim the same conditions of prosperous 1980's — 200,000 ha of sugarcane harvested —, it is valid to investigate revitalization possibilities for the sector. Norte Fluminense's sugarcane crop area (34,300 ha [69]) is equivalent (greater) to the total sugarcane crop are of countries like Jamaica, Ethiopia and Belize [170], playing an important part in their economies.

While the biorefinery concept ended up being the way out of instability for the agro-industries considered in the framework, industrial symbiosis has been seen as a potential solution to the revitalization of traditional businesses. It was argued to promote energy savings and sustainable energy production to improve profitability of farmers in Japan [166] and was applied in a project aimed at revitalizing a historical chemical site located in Bussi sul Tirino (Italy). In this case, the site faced obsolete capacity due to reduced demand and to the loss of competitiveness at a national and international levels [257].

6.6 The issue of scale

As it has been previously stated, this study put special attention on least productive regions of Brazilian sugarcane industry, which are responsible for the processing of 82 million tonnes of sugarcane in 97 facilities (source). This means less than 1 million tonnes of sugarcane processed per facility per year.

A typical sugarcane mill in Brazil is conventioned as processing 2 to 3 million tonnes of sugarcane per year, whereas in the most productive regions it can achieve 6 million tonnes per year. Therefore it is reasonable to assume that the least productive regions mostly comprise small scale sugarcane mills.

There are also units known as micro-distilleries a micro mills in Brazil, which operate in even lower scales. These industries however are less subjects to international market dynamics since they mainly rely on proprietary crops to produce higher valued food products as rapadura (brown sugar in tablet), brown sugar, cane syrup and sugarcane liquor (cachaça) [].

While most of the studies are focused on the most productive regions and with larger scale units, there is a universe to be explored with the minor scale units. Commercial sugarcane fractionation technologies already exist to operate at load levels departing from 10 tonne/h [**?**]. The potential of using the biorefinery concept is thus significant even in the less productive regions of Brazil and this opens a perspective of greater stability in the face of market reversals and national policies that are generally conceived under the perspective of larger scale production.

Biorefineries have been somewhat explored in the smaller scale, but there is still gap on how the industrial symbiosis approach has been applied to systems comprising smaller scale units. As further explorations of such topic is left as a recommendation for future work, a preliminary screening of industrial symbiosis on the small scale has been performed and is presented in Appendix **??**. It shows that most of the studies did not have small and medium enterprises (SMEs) as primary focus, being the concentration of SMEs in the research also an outcome. It confirms the necessity of further exploration in this domain.

6.7 A policy issue

The problem addressed in this thesis is directly related to policy making. It learns from spontaneous development' experiences to conceive a methodology capable of promoting similar developments in a planned way, which might be operationalized only through policies – which can be either public or private (through IS facilitation firms for instance). In this sense, the assessment of policy scenarios that are capable of driving the proposed outcomes is also a necessity.

Learning from past empirical experiences on industrial symbiosis in Brazil and given the prevalence of failures over successes, it can be concluded that there might be a gap on the policy making process in terms of approach, information or background that makes these developments stumble. We argue that this gap can be on the level of information over the actors involved in the process. There is often limited information about how the actors affected by the policies might behave throughout the policy vigour.

The general praxis is to rely on high level average-based information that do not capture specifities from the actors. Among these specifities are habits, cultural background, asymmetry of interests and other specific behavior affecting actions, interactions and decision-making processes.

In this sense, policy assessment methods that take these specifities into consideration beyond the average level, i.e. taking into account the heterogeneities in the actors level, are needed.

6.8 The prospects of a vision

The scenarios developed for this study can be understood as vision which to attain to in the development of plans, policies and further investigations. In this sense, the short-term scenario presents the vision of what to expect when a bagasse-based succinic acid facility is installed adjacent to the sugarcane mill to make use of its bagasse and CO_2. Besides the issues of cogeneration process upgrade and furnace burners adaptation to cope with straw and lignin, other points of attention can be drawn from that scenario.

The first point concerns the byproducts that are not recycled in the reference scenario. While in the scenario they can be simply considered as disposed in the environment, in the endeavour of materializing this vision, this issue might have to be addressed, which might mean that the new facility comprising the effluent treatment unit might have to be installed in the short term instead of in the long term.

Secondly, some application proposed in the mid-term scenario, — like the destination of the CO_2 to soft drinks manufacturers, the exchange of fusel oil with the distilled spirits facility, and the destination of the used yeast from the ethanol production to the animal feed producer — can also be implemented in the short run, since the materials and the facilities already operates in the region. It would demand though a more detailed assessment to verify: (1) the feasibility of the exchanges and (2) the willingness of the parties involved to negotiate and close a deal.

Another important point in the short term — and in the other scenarios as well — concerns the regulatory aspects over the reuse or recycling of each byproduct considered. It is very likely to happen that a synergy, even being economically attractive for both buyer and seller, can not be performed due to a regulation that do not allow such exchange. Indeed, the regulatory aspect is among the main obstacules to the operationalization of industrial symbioses worldwide <source>.

Regarding the mid-term scenario, the vision provided calls the attention to the destination of both used yeast from the ethanol and succinic acid production to the animal feed producer. Such use is well known and recommended in the literature for the ethanol-derived yeast, however, no conclusive information about this possibility was found for the succinic acid-derive yeast. In the scenario design, it was assumed that both would have similar properties and as such would have the same destination, but during the implementation process this point must be clarified. The destination of the succinic acid out of specification (*off-spec succinic acid* in Figure 5.9) to the surfactants' manufacturer also demands discussion. Given the value of the succinic acid in the market (approximately $2,000/tonne []), the frequency and the volume of the off-spec substance might not enable the exchange.

Finally, in the vision of the system in the long-term scenario, the interchangeable use of the filter cake from the sugar and succinic acid production units conforms a situation analog to that of the used yeast. Physico-chemical properties about the filter cake from the succinic acid facility were not available by the time the scenario was designed. Now concerning to the lube oil, it is not realistic to have a facility operating exclusively for the biorefinery, since it concerns a lower profit margin activity, demanding medium to large scale facilities to become economically feasible. The same is valid to the effluent treatment and biogas production units.

The visions provided by the scenarios developed using the methodological approach proposed can better inform decision and policy makers, researchers and practitioners about what to expect from the transition of a conventional sugarcane mill to an IS-based advanced biorefinery in a given location. The types information that can be obtained are:

- Extra investments that might be needed;
- Synergies planned for mid or long term in the scenarios but that can be implemented in the short term;
- New facilities (proposed for the long term) that can be better off installed in the short term (for instance, the effluent treatment facility);
- Synergies that are not likely to happen because of their low volume or low frequency of availability;
- New facilities of which operation might be more economic if shared with other industries in the local;
- Synergies that need further investigation over the real potential due to the unavailability of information over their properties by the time the scenario was developed; etc.

Indeed, all the propositions from the scenarios must be further investigated. Again, these propositions have to be regarded as visions, as guides to what a desired future might be, supporting the identification of opportunities and removal of barriers in the pathway towards it. Hence, an implementation process not strictly following what was conceived in the scenarios by no means invalidate it. On the contrary. It is the scenarios' very purpose to be studied, questioned and, if necessary, modified. This is what progress is all about.

Chapter 7

Conclusions and recommendations for future work

This chapter presents the final remarks of the thesis, re-stating the research questions and the respective answers provided throughout the document. The limitations and future works foreseen from the present research are also addressed in the final section.

Under the hypothesis that an industrial symbiosis-based biorefinery can lead to improved social, economic and environmental performances of Brazilian local agro-industry and surroundings, this thesis proposed a methodology to plan the transition of Brazilian sugarcane mills into advanced biorefineries using the industrial symbiosis approach.

Through the design of prospective scenarios, the case study on the Norte Fluminense region has shown that the methodology indeed allows the construct of frames for the gradual development of IS-based avanced biorefineries at the local scale. However, while benefits to the industry and its surroundings can be expected, the concrete usufruct of positive outcomes is highly context-dependent. The configuration of the symbiotic network is also critical since the use provided to the byproducts is the very source of value.

7.1 Recalling the research questions

The first research question regards the circumstances under which an IS-based biorefinery can be a means of improving the socioeconomic and environmental conditions of a given agro-industrial sector and its surroundings. This study has shown that such development is highly context-dependent, of which the stakeholders behaviors play a major rule.

The pathway devised to assess the theoretical potential for a sugarcane company in Brazil to become an industrial symbiosis-based biorefinery is based on the evolutionary path of the empirical cases uncovered. From a comparative analysis of their experience, it was possible to identify the factors that enabled their development, which were then used as criteria for the assessment. These enabling factors are either endogenous or exogenous.

- A volatile market due to increasing especulations over sugar prices that push the development of parallel markets for robustness and stability.
- An increasingly restrictive environmental regulation for protecting the environment and local territories.
- Stakeholders attitude in the face of a disadvantageous context, seeing failures as opportunities and turning weaknesses into strength through perseverance and investments on innovative solutions and technologies.
- Upstream partnerships to guarantee feedstock quality and supply and downstream partnerships providing destination to uncycled byproducts
- Massive investment on Research & Development to increase competitiveness and robustness through the creation of new processes and applications for products and byproducts.
- Appropriate timing characterized by a primary focus on developing internal efficiency and diversification, followed by the performance of external investment partnerships.

Theoretically, the more the sugarcane processing company can cope with such factors the greater is its potential to to become an industrial symbiosis-based biorefinery. Currently, there are at least three operating industrial symbiosis-based biorefineries: the Bazancourt-Pomacle Biorefinery (France), the Guangxi site of sugar and paper production of Shenzhen Huaqiang Holdings Co. Ltd., formely Guitang Group, (China); and the Wissington site of British Sugar (UK).

In Chapter 3, it was shown that the development of these biorefineries was spontaneous and gradual, without the establishment of a previous plan or coordinating party, implying that there was no design involved. Their current configuration emerged from a sum of factors that enabled such development, being the most relevant the strong focus on Research & Development and external factors like the increasing liberalization of the agro-industrial sector worldwide and regulatory measures demanding sustainable practices of agro-industrial activities nation- and continent-wide.

Under these circumstances, the sugar refineries investigated started a process of market diversification through the exploration of valuable uses for its byproducts. This process started from the inside out, with internal symbiosis being prioritized in the beginning and partnerships with other firms to consume remaining byproducts and further endeavors being carried out in the long run.

Learning from and adding to the methodological approaches for planning symbiotic industrial systems in Brazil [87, 132, 181, 278], and based on the conceptual framework uncovered, this thesis proposed a methodological approach for planning the development of industrial symbiosis-based biorefineries in Brazil from the current configuration of its sugarcane mills.

The main premisses of the methodology is the existence of a sugarcane mill under operation and the path- and context-dependent nature of such develop that impedes the provision of "one size fits all"-type of solution. It hence precinds a located approach where one particular company and its surroundings are assessed at a time. It is acknowledged however, that the interventions conceived are likely to affect other players in the surroundings, but this further investigation is left for future research in the topic.

The methodology conceived consists on the design and assessment of three consecutive scenarios for turning an existing sugarcane processing facility into an industrial symbiosis-based advanced biorefinery. The first scenario is the baseline over which the others are developed. It is referred as reference scenario and comprehends the characterization of the agro-industry, the inventory of byproducts and existing symbioses and the inventory of other productive activities carried out in the surroundings.

The short-term scenario is the second scenario to be developed, consisting of the proposition of primary and secondary internal symbioses. It represents approximately a 5-year timespan in which efficiency-driven and/or new businesses' investments are provided to happen. The mid-term scenario comprehends the interaction with existing productive activities conforming primary external symbiosis, while the long-term proposes the installation of new companies to perform secondary external symbioses. Hence, the mid- and long-term scenarios comprise the classical industrial symbiosis approach, according to which collaborative use and management of resources occurs between otherwise unrelated firms.

In the methodological approach conceived the third stage of the framework uncovered was split into two — primary external symbiosis and secondary external symbiosis. This was done as a mean to confer more sistematization to the planning process and also under the assumption that synergies with existing industries are likely to be accomplished before the installation of new businesses. But it acknowledged that in the "real world" such stages might superpose.

The second research question regarded the configurations that the network of an IS-based biorefinery would display in the least productive regions of the Brazilian sugarcane sector. This thesis presented the case study for the Norte Fluminense region, one of the least productive regions in the country. It showed that there are opportunities to provide alternative and more valuable destinations to at least twelve byproducts in the long term, potentially connecting hitherto unrelated existing businesses and attracting four new firms to the region. Also, three potential synergies identified could be implemented prior to the advanced biorefinery deployment. This indicates that, theoretically, and according to the technical aspect, there is potential for a industrial symbiosis-based biorefinery to occur in the region.

Regarding the system diversity, eight distinct industrial types can be part of the network (industrial surfactants, wax, adhesives, soft drinks, distilled spirits, and animal feed production units, lube oil re-refinery and effluent treatment/biogas production plant). This diversity gives a dimension of the social and economic dynamics that could be established in the region since each of these facilities has its own set of products and byproducts to be regionally sold or exchanged.

However, the assessment of the social enabling factors in the region have shown that there is a sensible difference on the attitude of the stakeholders — in comparison with the empirical cases — on dealing with adversities, perfoming investments and timing, so that the processes is not likely to happen spontaneously as it was observed in the empirical experiences.

The variety of potential applications that each byproduct can have implicate in the possibility of diverse configurations being conceived. It will mainly depend on the criteria underlining the development and on the quantity and type of byproducts involved. In this study, the criteria used was higher added value applications with the proposal of a bagasse-based succinic acid biorefinery, which made eighteen byproduct streams available to be explored. According to the methodology developed, at least three configurations would be possible, concerning the short-, mid- and long-term scenarios.

Since the local context is an input to the methodology, scenarios of the development of IS-based advanced biorefineries from existing sugarcane mill facilities can be conceived regardless of where they are inserted. Hence, the methodological approach proposed can be applied to different contexts and encompass different biorefining technologies. It provides visual material for comparing different perspectives and criteria, enabling a broader and deeper realization of (1) what such developments might demand, (2) the outcomes to be expected, and (3) if what was previously thought as appropriate is really desirable.

7.2 Recommendations for future work

As a recommendation for future work, this thesis suggests the expansion of the analysis of social impacts, including also indirect jobs and induced jobs. It is believed that the proposition of new economic activities in regions such as the Northern Fluminense has great potential of generating employment in support services such as supermarkets, banks, etc.

It is also suggested the more detailed analysis of the process, obtaining more representative parameters of units in less productive regions. Such detailing will allow a more precise estimation of the amount of resources available for the conformation of the industrial symbiosis network.

Finally, it is also suggested the replication of the study carried out in different regions and also the expansion of the scope to cover different types of biomass and different products and different routes of biorrefino. Each of these aspects can confer different configurations to industrial symbiosis networks. And this perspective allows a strategic approach on the part of the decision makers in programs of development more aligned with the natural vocations of each place.

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Appendix A

Event log about the facts and facts affecting the sugarcane industry of the Norte Fluminense region

The development of the sugarcane industry in Norte Fluminense traces back to the colonization of the Brazilian territory by Portugal. The first attempts to cultivate sugarcane happened still in the 16th century (in 1538 and 1958) [46], but got stable in the second half of the 18th century. In this period, the production was characterized by atomized small farmers and producers distributed throught the city of Campos dos Goytacazes.

There were 324 rudimentary mills and 4 ethanol distilleries in the region, each producing up to 7500 kg of sugar per year. Interestingly, sugar and ethanol production was performed by distinct producers and there was a relationship of rivalry between them [46]. The 18th century was also characterized by the growth of sugar production production in the Caribbean islands, Antilles, South Africa, Australia, etc., openning competition with the Brazilian production. In this period, Ayti was the major sugar producer in the world [217]. It was also in the 18th century that beetroot sugar refining was developed, being adopted throughout Europe in the 19th century.

The following images present a table with the sequence of events in the international, national, regional and local levels of Norte Fluminense. They were developed to increase the comprehension of the factors influencing its current state.

The table is also available on internet and can be freely accessed through the link: https://docs.google.com/spreadsheets/d/1kAUhNxXkZF8-kVW78S4prHqfQRtvU7-cgEu5uA6xFnU/edit?usp=sharing

*** Event log about the facts affecting the sugarcane industry of the Norte Fluminense region ***

Century	Year	Month (if available)	What happened	In which level?	Who did	As a response to what	Affecting what	Is it a policy?	Source
17th			**Colonization of the territory**	**Campos dos Goytacazes**	**Portugal**		**Brazilian history** **Local sugar and ethanol production**	**Yes**	**IBGE (2012a)**
16th	1538		First attempt to start sugarcane plantation in the region	Campos dos Goytacazes	Pero de Gois	International sugar demand Demand for cachaca for the acquisition of enslaved persons	Local sugar and ethanol production		Castro (2009)
16th	1558		Second attempt to start sugarcane plantation in the region	Campos dos Goytacazes	Gil de Gois	International sugar demand Demand for cachaca for the acquisition of enslaved persons	Local sugar and ethanol production		Castro (2009)
17th	1632		Part of the Sao Tome captaincy was ceded by the crown to 7 Portuguese captains	Campos dos Goytacazes	Portugal	Land abandonment by Gois family International sugar demand Demand for cachaca for the acquisition of enslaved persons	Local sugar and ethanol production	Yes	Castro (2009)

Figure A.1: Sequence of historical events in the Norte Fluminense's sugarcane sector development: 16th and 17th centuries.

*** Event log about t he facts affecting the sugarcane industry of the Norte Fluminense region ***									
Century	**Year**	**Month (if available)**	**What happened**	**In which level?**	**Who did**	**As a response to what**	**Affecting what**	**Is it a policy?**	**Source**
18th	**First 1700's**		**Growth of sugar production production in the Caribbean islands and in the Antilles, openning competition with the Brazilian production**	**International market**					**Pinheiro Machado apud UDOP**
18th	First 1700's		Ayti was major sugar producer	International market	French				
18th	**1747**		**Andreas Marggraf develops technique to produce sugar from beetroot**	**Prussia**	**Andreas Marggraf**				**Pinheiro Machado apud UDOP**
18th			New sugarcane production regions and new technologies are developed all over the world (South Africa, Mauritius and Réunion, Australia and in English, French or Dutch colonies)	International market					Pinheiro Machado apud UDOP
18th	**> 1750**		**Start stable sugarcane plantation in the region**	**Norte Fluminense**	**Portugal**	**International sugar demand Demand for cachaca for the acquisition of enslaved persons**		**Yes**	**Castro (2009)**
18th	> 1750		616 rudimentary sugar mills and 253 ethanol distilleries in the state, each producing up to 7500 kg of sugar per year	Rio de Janeiro State	Sugarcane mills	International sugar demand Demand for cachaca for the acquisition of enslaved persons	Local sugar and ethanol production		Castro (2009)
18th	> 1750		324 rudimentary mills and 4 ethanol distilleries in the state, each producing up to 7500 kg of sugar per year	Campos dos Goytacazes	Sugarcane mills	International sugar demand Demand for cachaca for the acquisition of enslaved persons	Local sugar and ethanol production		Castro (2009)
18th	1791		Start sugar production in the USA	United States	French expelled from Ayti				
19th	**1801**		**First sugar beet refinery opened**	**Prussia**	**Franz Karl Achard**				**https://en.wikipedia.org/wiki/Franz_Karl_Achard**
19th	1806		In 1806 Achard's plant was burned down by Napoleon's war and in 1810 it was rebuilt on a small scale. Embargoes by Napoleon kept cane sugar imports away from Germany and thus the growing and refining of sugar beets became highly important for the Prussian government.	Germany	Napoleon				https://en.wikipedia.org/wiki/Franz_Karl_Achard

Figure A.2: Sequence of historical events in the Norte Fluminense's sugarcane sector development: 18th century.

*** Event log about the facts affecting the sugarcane industry of the Norte Fluminense region ***									
Century	**Year**	**Month (if available)**	**What happened**	**In which level?**	**Who did**	**As a response to what**	**Affecting what**	**Is it a policy?**	**Source**
19th	**1808**		**Arrival of the Portuguese court in Brazil**	**Brazil**	**Portugal**	**Alliance between Spain and Portugal** **French invasion to Portugal**	**Brazilian history** **Local sugar and ethanol production**	**Yes**	
19th	> 1808		Loss of competitiveness of contraptions and human / animal traction	Norte Fluminense	Sugarcane mills	International sugar demand International sugar market Chegada da corte portuguesa no Brasil	Local sugar and ethanol production Former sugar and ethanol producers		Castro (2009)
19th	> 1808		Establishment of the real mill (with mills driven by hydraulic energy).	Campos dos Goytacazes	Sugarcane mills	International sugar demand International sugar market Chegada da corte portuguesa no Brasil	Local sugar and ethanol production Former sugar and ethanol producers		Castro (2009)
19th	> 1808		Establishment of steam engines.	Campos dos Goytacazes	Sugarcane mills	International sugar demand International sugar market Chegada da corte portuguesa no Brasil	Local sugar and ethanol production Former sugar and ethanol producers		Castro (2009)
19th	> 1808		Former sugar and ethanol producers gradually became sugarcane suppliers to the Engenhos a vapor	Campos dos Goytacazes	Former sugar and ethanol pro	Expansion of Steam Engines and reduction of number of contraptions Concentration process Emergence of senhores de engenho Stabilization of sugar prices not tolerable for small producers	Local sugar and ethanol production		Castro (2009)
19th	> 1808		Stabilization of non-bearable sugar prices for small producers	Brazil	International sugar market	(?) Increase in sugar supply in the market? New entrants?	Local sugar and ethanol production		Castro (2009)
19th	> 1808		Owners of engenho participated intensely in the public administration, with social, economic and political influence	Norte Fluminense	Sugarcane mills	Concentration of capital (?) Relationship with the Portuguese crown?	Norte Fluminense		Castro (2009)
19th	> 1808		Surgimento de fundicoes para fabrico de moendas e tachos de ferro	Norte Fluminense	(?) Private investors?	Expansao dos Engenhos a vapor e reducao do numero de engenhocas Processo de concentracao de capital Surgimento dos senhores de engenho Estabilizacao de precos do acucar nao suportavel p pequenos produtores	Norte Fluminense		Castro (2009)
19th	> 1808		Melhoria tecnologica na industria: uso de caldeiras, uso de bagaco no lugar de lenha, acondicionamento do acucar em sacos ao inves de caixas de madeira	Norte Fluminense	Sugarcane mills	Expansao dos Engenhos a vapor e reducao do numero de engenhocas Processo de concentracao de capital Surgimento dos senhores de engenho Estabilizacao de precos do acucar nao suportavel p pequenos produtores	Norte Fluminense		Castro (2009)

Figure A.3: Sequence of historical events in the Norte Fluminense's sugarcane sector development: 19th century (Arrival of the Portuguese court).

*** Event log about the facts affecting the sugarcane industry of the Norte Fluminense region ***									
Century	**Year**	**Month (if available)**	**What happened**	**In which level?**	**Who did**	**As a response to what**	**Affecting what**	**Is it a policy?**	**Source**
19th	> 1808		Melhoria tecnologica na lavoura: uso do arado	Norte Fluminense	Sugarcane farms	Expansao dos Engenhos a vapor e reducao do numero de engenhocas Processo de concentracao de capital Surgimento dos senhores de engenho Estabilizacao de precos do acucar nao suportavel p pequenos produtores	Norte Fluminense		Castro (2009)
19th	1811		Sugar production from beetroot is started in France and its colonies	France	Napoleon				https://en.wikipedia.org/wiki/Franz_Karl_Achard
19th	**1822**		**Brazil's Independence**						
19th	1827		700 Engenhocas (rudimentary mills) 1 Engenho a vapor	Campos dos Goytacazes	Sugarcane mills	International sugar demand International sugar market Chegada da corte portuguesa no Brasil	Local sugar and ethanol production Former sugar and ethanol producers		Castro (2009)
20th	1852		307 Engenhocas (rudimentary mills) 56 Engenho a vapor	Campos dos Goytacazes	Sugarcane mills	International sugar demand International sugar market Chegada da corte portuguesa no Brasil	Local sugar and ethanol production Former sugar and ethanol producers		Castro (2009)

Figure A.4: Sequence of historical events in the Norte Fluminense's sugarcane sector development: 19th century (Independence of Brazil).

***** Event log about the facts affecting the sugarcane industry of the Norte Fluminense region *****

Century	Year	Month (if available)	What happened	In which level?	Who did	As a response to what	Affecting what	Is it a policy?	Source
19th	**1857**		**Elaborado programa de modernizacao da producao de acucar no Brasil**	**Brasil**	**National government (D. Pedro II)**		**Local sugar and ethanol production** **Former sugar and ethanol producers**	**Yes**	**Castro (2009)** **Pinheiro Machado *apud UDOP***
19th	1857		Elaboracao de novo modelo de producao: Engenhos centrais (novo modelo de producao). 57 foram aprovados mas apenas 12 foram implantados.	Brasil	National government		Local sugar and ethanol production Former sugar and ethanol producers	Yes	Castro (2009) Pinheiro Machado *apud UDOP*
	1857		Cuba is the major sugar producer in the world (25% perent of total production)	International market	Cuba				
	1857		Beetroot sugar production (EUA and Europe) was 36% of total world production	International market	USA and Europe				
19th	1861		267 Engenhocas (rudimentary mills) 68 Engenho a vapor	Campos dos Goytacazes	Sugarcane mills	International sugar demand International sugar market Chegada da corte portuguesa no Brasil	Local sugar and ethanol production Former sugar and ethanol producers		Castro (2009)
19th	1872		207 Engenhocas (rudimentary mills) 113 Engenho a vapor	Campos dos Goytacazes	Sugarcane mills	International sugar demand International sugar market Chegada da corte portuguesa no Brasil	Local sugar and ethanol production Former sugar and ethanol producers		Castro (2009)
	1874		5% da producao mundial do mundo advinha do Brasil. Isso correspondia a 2,64 milhoes de toneladas de acucar.	International market	Sugarcane mills				Pinheiro Machado apud UDOP
19th	1877		Implantacao do primeiro engenho central na regiao	Norte Fluminense	(?)National government?	Elaboracao de novo modelo de producao: Engenhos centrais (novo modelo de producao)	Local sugar and ethanol production Former sugar and ethanol producers	Yes	Castro (2009) Pinheiro Machado apud UDOP
19th	1878		Implantacao do segundo engenho central na regiao	Norte Fluminense	(?)National government?	Elaboracao de novo modelo de producao: Engenhos centrais (novo modelo de producao)	Local sugar and ethanol production Former sugar and ethanol producers	Yes	Castro (2009)
19th			Fechamento da maioria dos engenhos centrais.	Brasil	Sugarcane mills	Fracasso do modelo de engenho central "O desconhecimento dos novos equipamentos, a falta de interesse dos fornecedores, que preferiam produzir aguardente ou mesmo açúcar pelos velhos métodos"	"Os próprios fornecedores dos equipamentos acabaram por adquiri-los e montar suas indústrias de processamento de açúcar. A maioria das novas indústrias estava no Nordeste e em São Paulo e passaram a ser chamadas de "usinas de açúcar".		Castro (2009) Pinheiro Machado apud UDOP

Figure A.5: Sequence of historical events in the Norte Fluminense's sugarcane sector development: 19th century (Modernization of sugar production in Brazil).

*** Event log about the facts affecting the sugarcane industry of the Norte Fluminense region ***									
Century	Year	Month (if available)	What happened	In which level?	Who did	As a response to what	Affecting what	Is it a policy?	Source
19th			Surgimento das usinas	Norte Fluminense		International sugar demand International sugar market (What else?)			Castro (2009)
19th	1881		120 Engenhocas (rudimentary mills) 252 Engenho a vapor 5 Usinas	Campos dos Goytacazes	Sugarcane mills	International sugar demand International sugar market Chegada da corte portuguesa no Brasil	Local sugar and ethanol production Former sugar and ethanol producers		Castro (2009)
19th	**1888**		**Abolition of slavery**	**Brasil**	**National government**	**Abolitionist movement** **Need for cosumer market => Not in the reference**		**Yes**	**Castro (2009)**
			o governo brasileiro incentivou a vinda de europeus para suprir a mão-de-obra necessária às fazendas de café, no interior paulista	Brasil	National government	Abolitionist movement Need for cosumer market => Not in the reference	National sugar and ethanol production structure	Yes	Pinheiro Machado apud UDOP
			Os imigrantes, de maioria italiana, adquiriram terra e grande parte optou pela produção de aguardente a partir da cana. Inúmeros engenhos se concentraram nas regiões de Campinas, Itu, Moji-Guaçu e Piracicaba.	Brasil	Imigrants				
19th	**1889**		**Brazil becomes a Federative Republic**	**Brasil**					
	1900		O açúcar derivado da cana não fazia frente ao de beterraba (em 1900 ultrapassava mais de 50% da produção mundial).	International market	Sugarcane mills	Atraso tecnologico. 100 anos para comecar a modernizar.			
20th			Production concentration went on	Norte Fluminense	Sugarcane mills		Local sugar and ethanol production structure		Castro (2009)
20th			Modern mills acquired land for high prices	Norte Fluminense	Sugarcane mills		Local sugar and ethanol production structure		Castro (2009)
20th			Modern mills upgraded their industrial park	Campos dos Goytacazes	Sugarcane mills		Local sugar and ethanol production		Castro (2009)
20th	1905		17 Engenhos centrais 10 usinas 22 mil toneladas de acucar e 5 milhoes de litros de cachaca por ano	Campos dos Goytacazes	Sugarcane mills		Local sugar and ethanol production		Castro (2009)

Figure A.6: Sequence of historical events in the Norte Fluminense's sugarcane sector development: 19th century (Development of mills|Abolition of Slavery|Proclamation of Republic).

*** Event log about the facts affecting the sugarcane industry of the Norte Fluminense region ***									
Century	**Year**	**Month (if available)**	**What happened**	**In which level?**	**Who did**	**As a response to what**	**Affecting what**	**Is it a policy?**	**Source**
	1914		**A 1ª Grande Guerra, iniciada em 1914, devastou a indústria de açúcar européia.**	**International market**	**Sugarcane farms** **Sugarcane mills**		**International sugar and ethanol production structure**		**Pinheiro Machado apud UDOP**
			Aumento do preço do acucar no mercado mundial. Incentivo aa construção de novas usinas no Brasil (notadamente em São Paulo, onde muitos fazendeiros de café desejavam diversificar seu perfil de produção)	Brasil		A 1ª Grande Guerra, iniciada em 1914, devastou a indústria de açúcar européia.	National sugar and ethanol production structure		Pinheiro Machado apud UDOP
20th	1914		Instalacao da Estacao Experimental do Rio de Janeiro	Campos dos Goytacazes			Local sugar and ethanol production		Castro (2009)
20th	1925		Construcao de varias usinas fora de campos dos goytacazes	Norte Fluminense	Sugarcane mills		Local sugar and ethanol production		Castro (2009)
20th	**1920-30**		**Estabelecimento de cotas de producao de acucar e etanol pelo governo federal**	**Brasil**	**National government**			**Yes**	**Castro (2009)**
20th	1920-30		Due to the creation of quotas, Campos dos Goytacazes becomes the greatest sugar producer in the country	Campos dos Goytacazes	National government				Castro (2009)

Figure A.7: Sequence of historical events in the Norte Fluminense's sugarcane sector development: 20th century (First World War).

*** Event log about the facts affecting the sugarcane industry of the Norte Fluminense region ***									
Century	Year	Month (if available)	What happened	In which level?	Who did	As a response to what	Affecting what	Is it a policy?	Source
	1929		1929 Crisis (The great depression)	International market					Moraes (2007)
20th	1933		Instituto do Acucar e do Alcool (IAA) is created	Brasil	National government		National sugar and ethanol industry		
20th			Sugarcane sector started a self-organization process to defend its interests	Norte Fluminense	Sugarcane mills		Local sugar and ethanol production structure		Castro (2009)
20th	1934		Fundacao do Sindicato da Industria do Acucar nos Estados do Rio de Janeiro	Estado do Rio de Janeiro	Sugarcane mills	Need for organized structure to guarantee interests of the sector	Local sugar and ethanol production structure		Castro (2009)
20th			Sindicato passa a chamar-se Sindicato da Industrial e da Refinacao do Estado do Rio de Janeiro	Estado do Rio de Janeiro	Sindicato				Castro (2009)
20th	1938-39		14% da producao de acucar nacional era advinda do Estado do Rio de Janeiro (terceiro maior produtor do pais)	Estado do Rio de Janeiro	Sugarcane mills				Castro (2009)
20th	1941		Banco dos Lavradores is created	Estado do Rio de Janeiro	Farmers				Castro (2009)
20th	1943		Cooperativa Fluminense dos Usineiros Ltda. is created (later on became Cooperativa Fluminense dos Produtores de Acucar e Alcool Ltda.)	Norte Fluminense	Sugarcane mills				Castro (2009)
20th	1945		Sindicato Agricola de Campos is created	Campos dos Goytacazes					Castro (2009)
20th	Mid 1940's		Sugarcane mills upgraded their units to increase production. Some imported equipment.	Norte Fluminense	Sugarcane mills				Castro (2009)
20th	1946		Revisao geral das cotas de producao de acucar de usina atribuidas a cada estado	Brasil	National government		Sugarcane farmers Sugarcane mill owners	Yes	Decreto-lei n 9827 10/09/1946 (http://www.planalto.gov.br/ccivil_03/decreto-lei/Del9827.htm)
20th	1947		The 1947 General Agreement on Tariffs and Trade (GATT) applied to agriculture, but in practice, the contracting parties excluded this sector from application of the principles set out in the general agreement.	World					Schieb (2015)
20th	1948		Banco dos Lavradores becomes COOPERCREDI - Cooperativa de Credito dos Lavradores de Cana de Acucar do Estado Rio de Janeiro Ltda.	Estado do Rio de Janeiro	Sugarcane farms	Need to improve the access to credits for funding the crops			Castro (2009)
20th	1948		Sindicato Agricola de Campos becomes ASFLUCAN - Associacao Fluminense dos Plantadores de Cana	Norte Fluminense	Sugarcane farms				Castro (2009)
20th			Hospital dos Plantadores de Cana is created	Norte Fluminense	Sugarcane farms				Castro (2009)

Figure A.8: Sequence of historical events in the Norte Fluminense's sugarcane sector development: 20th century (The great depression of 1929).

*** Event log about t he facts affecting the sugarcane industry of the Norte Fluminense region ***									
Century	**Year**	**Month (if available)**	**What happened**	**In which level?**	**Who did**	**As a response to what**	**Affecting what**	**Is it a policy?**	**Source**
20th			Hospital dos Plantadores de Cana is created	Norte Fluminense	Sugarcane farms				Castro (2009)
20th			COOPERFLU - Cooperativa Fluminense dos Produtores de Acucar e Alcool is created	Norte Fluminense	Sugarcane mills	Need to get loans from the Instituto do Acucar e do Alcool (availability public funds)	Sugarcane mills in the offnseasons		Castro (2009)
20th			COOPERFLU was responsible for selling the sugar from the cooperated mills	Norte Fluminense	Sugarcane mills		Sugarcane farms		Castro (2009)
20th	Final 1950's		Some sugarcane mills in the region started being bought by sugarcane mill owners from NE region	Norte Fluminense	Sugarcane mills		Local sugar and ethanol production		Castro (2009)
20th			Sugarcane sector in the region starts to lose markets due to competitio with SP and NE region	Norte Fluminense		"defasagem tecnologica das industrias, gestao ineficiente dos recursos produtivos e baixa produtividade das lavouras	Local sugar and ethanol production		Castro (2009)
20th			500 to 2500 tons of sugarcane per day was the average capacity of sugarcane mills in the region (90500 to 452000 tons of sugarcane processed per year)	Norte Fluminense	Sugarcane mills		Local sugar and ethanol production		Castro (2009)
20th	Until 1960's		100 kg of sugar per ton of sugarcane was the average yield	Norte Fluminense	Sugarcane mills		Local sugar and ethanol production		Castro (2009)
20th	1970		21 usinas em operacao 14 usinas filiadas aa COOPERFLU	Campos dos Goytacazes	Sugarcane mills			No	Castro (2009)
20th	First 1970's		56% da cana processada era de plantadores de cana O restante era das proprias usinas	Norte Fluminense	Sugarcane mills	Abundancia de cana	Sugarcane farms Local sugar and ethanol production		Castro (2009)
20th	1971		High price of sugar in the international market	International market					
20th	1971		87,3 kg of sugar per ton of sugarcane was the average yield	Norte Fluminense	Sugarcane mills		Local sugar and ethanol production		Castro (2009)
20th	1972		89,4 kg of sugar per ton of sugarcane was the average yield	Norte Fluminense	Sugarcane mills		Local sugar and ethanol production		Castro (2009)
20th	1973		88,9 kg of sugar per ton of sugarcane was the average yield	Norte Fluminense	Sugarcane mills		Local sugar and ethanol production		Castro (2009)
20th	1973		COOPERFLU was authorized to obtain external loan of US$ 30 million	Norte Fluminense	National government			Yes	Castro (2009)
20th	1970's		Part of planted cane was not harvested due insufficient capacity to do so	Norte Fluminense	Sugarcane mills	Abundancia de cana	Sugarcane farms Local sugar and ethanol production		Castro (2009)
20th	**1970's**		**< 200 thousand ha of sugarcane crops with average yield of 40 to 50 tons per ha**	**Norte Fluminense**	**Sugarcane farms**		**Local sugar and ethanol production**		**Castro (2009)**
20th	1970's		Stimulus to increased production through industrial park upgrade	Brasil	National government	High price of sugar in the international market	National sugar and ethanol industry	Yes	Castro (2009)

Figure A.9: Sequence of historical events in the Norte Fluminense's sugarcane sector development: 20th century (...).

*** Event log about the facts affecting the sugarcane industry of the Norte Fluminense region ***									
Century	**Year**	**Month (if available)**	**What happened**	**In which level?**	**Who did**	**As a response to what**	**Affecting what**	**Is it a policy?**	**Source**
20th	>1970		Improvements occurred: - disappearance of firewood burn for more efficient boilers burning bagasse - new mills arrangements - use of shredders - embebicao mais eficiente - clarification methods improvement - more efficient evaporators and vaccuum - hire of technical personnel - like chemists - logistics changes for sugarcane transportation - rail and animal for road - mechanized shipment of sugarcane	Norte Fluminense	Sugarcane mills	Stimulus to increased production through industrial park upgrade	Local sugar and ethanol production		Castro (2009)
20th	1970's		Laws and guidelines to allow mergers and acquisitions of sugarcane mills and the sources of fund	Brasil	National government		Small (unproductive) sugarcane mills	Yes	Castro (2009)
20th			First merger: Santa Maria and Santa Isabel mills	Norte Fluminense	Sugarcane mills	Laws and guidelines to allow mergers and acquisitions of sugarcane mills and the sources of fund	Local sugar and ethanol production structure		Castro (2009)
	1973		First petroleum crisis	World					
20th	1974		92,0 kg of sugar per ton of sugarcane was the average yield	Norte Fluminense	Sugarcane mills		Local sugar and ethanol production		Castro (2009)

Figure A.10: Sequence of historical events in the Norte Fluminense's sugarcane sector development: 20th century (...).

*** Event log about the facts affecting the sugarcane industry of the Norte Fluminense region ***									
Century	**Year**	**Month (if available)**	**What happened**	**In which level?**	**Who did**	**As a response to what**	**Affecting what**	**Is it a policy?**	**Source**
20th	**1974**		**Petroleum reserves discovered at the Campos basin**	**Norte Fluminense**	**Federal government**	**National energy demand (?)**	**Norte Fluminense**	**Yes**	
	1975		88,4 kg of sugar per ton of sugarcane was the average yield	Norte Fluminense	Sugarcane mills		Local sugar and ethanol production		Castro (2009)
	1975		Sugarcane mill owners started to notice the lack of investment on the sugarcane crops	Norte Fluminense	Sugarcane mills	Unavailability of feedstock	Local sugar and ethanol production		Castro (2009)
	1975		**Lancamento do Proalcool**	**Brasil**	**National government**	**Oil and Gas crisis**	**National sugar and ethanol industry**	**Yes**	**Castro (2009)**
	1976		COOPERPLAN - Cooperativa Mista dos Plantadores de Cana is created	Norte Fluminense	Sugarcane farms	Need for technical (mechanization) services in the farms	Sugarcane production		Castro (2009)
	1978		Implantacao do pagamento de cana pela qualidade (teor de sacarose).	Alagoas				Yes	Costa (2009)
	>1970		3000 to 10000 tons of sugarcane per day was the average capacity of the new or upgraded sugarcane mills (543000 to 1810000 tons of sugarcane processed per year)	Norte Fluminense	Sugarcane mills	Stimulus to increased production through industrial park upgrade	Local sugar and ethanol production		Castro (2009)
	>1970		Greater use of trucks instead of wagons to transport the sugarcane	Norte Fluminense	Sugarcane farms	Sugarcane mills' need of higher volume in order to avoid interruptions in the production process.	Sugarcane farms		Castro (2009)
	>1970		Damage to sugarcane crops and roads (when existing)	Norte Fluminense	Sugarcane farms	Greater use of trucks instead of wagons to transport the sugarcane	Logistic infrastructure Local sugar and ethanol production		Castro (2009)
	>1970		Operational problems led some mills to require constant monetary withdraws from COOPERFLU	Norte Fluminense	Sugarcane mills	Operational problems after upgrades	Local sugar and ethanol production structure		Castro (2009)
	1979		Second petroleum crisis						
	> 1980's		Demais estados implantam pagamento de cana pela qualidade (teor de sacarose).	Brasil		Implantacao do pagamento de cana pela qualidade em Alagoas em 1978		Yes	Costa(2009)
	1981		COOPERPLAN buys distillery - first sugarcane mill owned by sugarcane farmers	Norte Fluminense	Sugarcane farms		Local sugar and ethanol production structure		Castro (2009)
			Sugarcane mills stopped paying debts and taxes.	Norte Fluminense	Sugarcane mills	Operational problems after upgrades	Local sugar and ethanol production		Castro (2009)
			COOPERFLU acquires other loan of US$ 70 million (through IAA) to pay previous non-paid loan of US$ 30 million	Norte Fluminense	Sugarcane mills	Incapacity to pay previous loan	Local sugar and ethanol production	Yes	Castro (2009)

Figure A.11: Sequence of historical events in the Norte Fluminense's sugarcane sector development: 20th century (Discovery of petroleum in Norte Fluminense).

*** Event log about the facts affecting the sugarcane industry of the Norte Fluminense region ***									
Century	**Year**	**Month (if available)**	**What happened**	**In which level?**	**Who did**	**As a response to what**	**Affecting what**	**Is it a policy?**	**Source**
	1985		COOPERFLU's debt is US$ 150 million	Norte Fluminense	Sugarcane mills	Incapacity to pay previous loan and acquisition of other loan	Local sugar and ethanol production		Castro (2009)
20th	Mid 1980's		Peak of sugarcane production: 8 million tons in one season	Campos dos Goytacazes	Sugarcane farms		Sugarcane mill owners	No	Costa, Ponciano et al (2009)
	Mid 1980's		Several mills left COOPERFLU or went bankrupt	Norte Fluminense	Sugarcane mills	COOPERFLU's incapacity to pay previous loan and acquisition of other loan	Local sugar and ethanol production		Castro (2009)
	1986		COOPERFLU is discontinued	Norte Fluminense	Sugarcane farms				
20th	> Mid 1980's		Decline and stagnation of sugarcane production	Norte Fluminense	Sugarcane farms	Operational problems after upgrades Lack of investiment on crop improvement	Sugarcane mill owners	No	Costa, Ponciano et al (2009)
	> Mid 1980's		Deactivation of some sugarcane mills.	Norte Fluminense	Sugarcane mills	Operational problems after upgrades	Local sugar and ethanol production		Castro (2009)
	> Mid 1980's		Acquisition of some sugarcane mills by others (with better performance)	Norte Fluminense	Sugarcane mills	Operational problems after upgrades	Local sugar and ethanol production		Castro (2009)
	> Mid 1980's		Sale of production quotas to other sugarcane mills	Norte Fluminense	Sugarcane mills	Operational problems after upgrades	Local sugar and ethanol production		Castro (2009)
			12 million tons of sugarcane per season was the total processing capacity of the region	Norte Fluminense	Sugarcane mills	Installed processing capacity	Local sugar and ethanol production		Castro (2009)
	Final 1980's		7 million tons of sugarcane per season was the average processing	Norte Fluminense	Sugarcane mills	No change on planted area and productivity of sugarcane crops	Local sugar and ethanol production		Castro (2009)
	Final 1980's		**200 thousand ha of sugarcane crops with average yield of 40 to 50 tons per ha**	**Norte Fluminense**	**Sugarcane farms**		**Local sugar and ethanol production**		**Castro (2009)**
	Final 1980's		55% to 65% of industrial idleness in the sugarcane mills	Norte Fluminense	Sugarcane mills	Unavailability of feedstock	Local sugar and ethanol production		Castro (2009)
	Final 1980's		Sao Paulo extended sugarcane crops area	Sao Paulo	Sugarcane farms				Castro (2009)
	Final 1980's		End of private credit. Increased dependence on governmental incentives	Norte Fluminense	Sugarcane sector	Decline and stagnation of sugarcane production	Local sugar and ethanol production		Castro (2009)
	Final 1980's		Equipment manufacturers in the region went bankrupt	Norte Fluminense	Equipment suppliers	Decline and stagnation of sugarcane production	Local sugar and ethanol production		Castro (2009)
	Final 1980's		50% of idleness of sugarcane mills industrial park	Norte Fluminense	Sugarcane mills	Decline and stagnation of sugarcane production	Local sugar and ethanol production		Castro (2009)
	Final 1980's		Unemployment in the sector created "poverty belts" in the municipalities	Norte Fluminense	Sugarcane sector	Decline and stagnation of sugarcane production	Local social structure		Castro (2009)

Figure A.12: Sequence of historical events in the Norte Fluminense's sugarcane sector development: 20th century (...).

*** Event log about the facts affecting the sugarcane industry of the Norte Fluminense region ***									
Century	Year	Month (if available)	What happened	In which level?	Who did	As a response to what	Affecting what	Is it a policy?	Source
	1988		Promulgacao da Constituicao Federal de 1988	Brasil	National government				
	1990's		Deregulation of the sugarcane sector	Brasil	National government		National sugar and ethanol industry	Yes	Castro (2009)
	1990		IAA was discontinued	Brasil	National government		National sugar and ethanol industry	Yes	Castro (2009)
	1990		Lei Organica	Campos dos Goytacazes	Municipality		Campos dos Goytacazes	Yes	Procuradoria geral do municipio (2007)
	1990		> 200 thousand ha of sugarcane crops with average yield of 40 to 50 tons per ha	Norte Fluminense	Sugarcane farms		Local sugar and ethanol production		Castro (2009)
	1994		Sindicato da Industrial e da Refinacao do Estado do Rio de Janeiro is discontinued	Estado do Rio de Janeiro	Sugarcane mills				
	1994		In 1994, the Marrakech agreement gave a new multilateral frame for the progressive deregulation of agriculture. At this time agriculture benefitted from its own agreement, the Agreement on Agriculture.	World					Schieb (2015)
	1996		Instituicao dos planos anuais de safra para divulgacao dos volumes anuais de acucar e alcool para o abastecimento nacional e formacao de estoque de seguranca	Brasil	National government		Sugarcane farmers Sugarcane mill owners	Yes	Lei n 9362 de 13/12/1996 (http://www.planalto.gov.br/ccivil_03/leis/L9362.htm)
	1990's		COOPERCREDI receives support from Central Bank	Norte Fluminense	National government			Yes	
	1998		Implantacao do pagamento de cana pelo ATR.	Sao Paulo	Sugarcane mills Sugarcane farms			No	Costa(2009)
	1999		COOPERCREDI is discontinued	Norte Fluminense	Sugarcane farms				
	1999		Criacao do G-20	International market					
	1999		Criacao do CONSECANA (Conselho de Produtores de Cana-de-açúcar, Açúcar e Etanol do Estado de São Paulo)	Sao Paulo	Sugarcane mills Sugarcane farms	Deregulation of the sugarcane sector	National sugar and ethanol industry	No	https://www.consecana.com.br/formacao.asp
	>1999		Surgimento dos atravessadores (compradores) de cana	Norte Fluminense	Intermediarios	Desregulamentacao do setor	Sugarcane farmers Sugarcane mill owners	No	Brunoro Costa (2005) e Athayde (2009)
	2000		Reducao da area rural do ERJ de 40% para 11%	Estado do Rio de Janeiro	Farmers		Sugarcane mill owners	No	Rocha, Rodrigues et al (2010)
	2001		Criacao do Fundo de Desenvolvimento de Campos (Fundecam)	Campos dos Goytacazes	Municipality		Sugarcane farmers Sugarcane mill owners	Yes	Costa, Ponciano et al (2009)
	2001		Criacao do Fundo de Desenvolvimento da Cana (Fundecana)	Campos dos Goytacazes	Municipality		Sugarcane farmers Sugarcane mill owners	Yes	Costa, Ponciano et al (2009)
	2002		Holding J. Pessoa buys sugarcane mills Quissama and Santa Cruz	Norte Fluminense	External investor			No	Castro (2009)
	2000's		Holding J. Pessoa discontinues sugarcane mill Quissama		External investor			No	Castro (2009)

Figure A.13: Sequence of historical events in the Norte Fluminense's sugarcane sector development: 20th century (Brazilian Constitution of 1988).

*** Event log about the facts affecting the sugarcane industry of the Norte Fluminense region ***									
Century	Year	Month (if available)	What happened	In which level?	Who did	As a response to what	Affecting what	Is it a policy?	Source
	2002		COAGRO creation	Campos dos Goytacazes	Sugarcane farms	Criation Fundo de Desenvolvimento de Campos (Fundecam)			Costa, Ponciano et al (2009) Castro (2009)
	2004		Implantacao da Policam para a producao de goma xantana	Campos dos Goytacazes					Costa, Ponciano et al (2009) Francisco (2009)
	2006	August	Implantacao da HC Sucroquimica na Usina Paraiso para producao de solventes n-butanol e acetona	Campos dos Goytacazes					Costa, Ponciano et al (2009) Francisco (2009)
			Implantacao da Alcoolquimica Canabrava para a producao de etanol	Campos dos Goytacazes					Costa, Ponciano et al (2009)
21st	2007		Lei de Uso e Ocupacao do Solo foi promulgada	Campos dos Goytacazes	Municipality			Yes	Procuradoria geral do municipio (2007)
	2007		Lei de Parcelamento do Solo foi promulgada	Campos dos Goytacazes	Municipality			Yes	Procuradoria geral do municipio (2007)
	2007		Lei de Perimetros Urbanos	Campos dos Goytacazes	Municipality			Yes	Procuradoria geral do municipio (2007)
	2010		33% dos royaties e participacao especial para municipios do RJ vao para Campos	Campos dos Goytacazes	National government	O&G production in the Campos basin	Campos dos Goytacazes	Yes	Fundacao Ceperj (2012)
	2010		Producao de O&G representam 70,3% do valor adicionado total do municipio	Campos dos Goytacazes	O&G industry	O&G production in the Campos basin	Campos dos Goytacazes	No	Fundacao Ceperj (2012)
	2010		Cultivo de cana de acucar tem 45,5% de participacao no valor adicionado da agropecuaria	Campos dos Goytacazes	Sugarcane farms	Sugarcane production	Sugarcane mills	No	Fundacao Ceperj (2012)
	2010		Area dedicada ao cultivo da cana de acucar reduziu 36% nos 10 anos predecessores	Campos dos Goytacazes	Sugarcane farms	Decline/stagnation of sugarcane industry; increase of production costs due to climate factors (cause or consequence?)	Sugarcane mills	No	IBGE (2012)
	2010		5,4 milhoes t/safra de Capacidade de processamento de cana	Campos dos Goytacazes	Sugarcane mills	Capacity upgrade New units construction	Local sugar and ethanol production	No	MAPA (2012) Batista (2012) Costa, Ponciano et al (2009)
	2010		57,5%: fator de capacidade media nas usinas de cana de acucar	Campos dos Goytacazes	Sugarcane mills	Sugarcane availability	Local sugar and ethanol production Sugarcane mills' productivity	No	MAPA (2012) Batista (2012) Costa, Ponciano et al (2009)
	2010		2,2 milhoes t/safra de cana de acucar disponivel	Campos dos Goytacazes	Sugarcane farms	Decline/stagnation of sugarcane industry; increase of production costs due to climate factors (cause or consequence?)	Sugarcane mills	No	
	2012		Usina Canabrava comecou a operar	Campos dos Goytacazes		Investment on new sugarcane mill unit	Local sugar and ethanol prodution	No	UDOP (2012)
	2012		4 usinas em operacao	Campos dos Goytacazes	Sugarcane mills	Sugarcane availability	Local sugar and ethanol prodution	No	Coutinho (2012) MAPA (2012) Batista (2012)
	2013		Grupo MPE compra Usina Sapucaia	Campos dos Goytacazes	External investor				

Figure A.14: Sequence of historical events in the Norte Fluminense's sugarcane sector development: 20th century (Creation of COAGRO in 2002).

Appendix B

Detailed description of byproducts' applications

Byproducts from COAGRO

Several applications were mapped for the byproducts identified. This section details each of them in order to understand the current stage of development. Their stage of development will set the design of the scenarios since, for instance, applications in theoretical stage are not likely to be implementable in the short term. The Technology Readiness Level is the parameter used to classify the stage of development of each application.

Bagasse applications

Applications of bagasse other than as fuel for heat and power production represent a very small fraction of its current usage. However, they are still relevant given the variety of contexts where the sugarcane industry is deployed in the country, the uncertainties around future sugar and ethanol markets' dynamics, and the need to understand the possibilities for the design of symbiotic networks.

Animal feed The use of sugarcane bagasse for animal feed is known since the 1980's. It can be done either by hydrolyzing the bagasse with acetic acid or mixing it with caustic soda, yeast, mineral salts and urea to become digestible to cattle [72].

Biofuels, polymers and chemicals These are the most recent developments in terms of applications for sugarcane bagasse and the main competitors to its traditional use for surplus electricity production [92].

Fertilizer Sugarcane bagasse can also be used as fertilizer either *in natura* or mixed with filter cake [40].

Pulp and paper The use of sugarcane bagasse to produce cellulosic pulp has been practiced for over 60 years [297]. China, India and Colombia have tradition in this application [293], while in Brazil this use is little explored. Bagasse fibers are similar to eucalyptus' — main raw material of Brazilian paper and pulp industry — and their use for paper production prescinds the costs and impacts of forest crops. The technology is then mature and commercially available.

Straw

The use of sugarcane straw has been enabled by mechanized of harvesting. Before that, the practice of burning the crop destroyed this byproduct [72]. Due to their structural similarities, straw can have the similar applications of the bagasse.

Biofuels, polymers and chemicals These are the most recent developments in terms of applications for sugarcane straw.

Fertilizer Sugarcane straw can not be 100% removed from the fields as it is important to nourish the planting area, maintain soil moisture, control weeds and prevent soil erosion [293]. A fraction around 20-50% of the straw produced has to remain in the fields for this purpose [201, 293].

Pulp and paper The use of sugarcane straw to produce pulp and paper is less traditional than that of bagasse but it is also a commercially available technology. Recently, the first sugarcane straw-based cellulosic pulp manufacturer started its operation in Brazil. In this unit, the straw is collected from suppliers in the surroundings and cold-pretreated with a bio-dispersant to separate the lignin from the cellulose.

Sugarcane leaves and tips

It corresponds to that wad of leaves at the end of the plant, which is eliminated during cutting [134]. The exploration of the value of sugarcane leaves tips is also enabled by harvest mechanization.

Animal feed Such as with the bagasse, sugarcane tips can also be used as silage for animal feed, especially during the winter [134]. For this purpose, they are shredded and stored in silos for conservation through fermentation.

Bio-actives The leaves of sugarcane contains valuable substances, or bio-actives, for the industries of food suplements, pharmaceuticals and cosmetics. These bio-actives are steroids, terpenes and flavonoids [81].

Steroids Steroids are fat soluble (liposoluble) compounds — found in animals, fungi and plants —, that have a basic structure of 17 carbon atoms arranged in four rings connected together. They constitute important components of cell membranes affecting their fluidity and serve as signaling molecules which activate steroid hormone receptors in these organisms.

Therapeutically, corticosteroids are used as immunosuppressants in the treatment of autoimmune diseases and in transplant surgery. Anabolic steroids are derived from the male hormone testosterone. They trigger the deposition of protein in the tissues and were once used to aid in convalescence. They are sometimes ingested by athletes and weight lifters because of their muscle building and strengthening properties, but can cause serious damage to the liver. Steroids are also the active ingredients in most orally administered birth control pills. In various specialties, steroids called hormonal anti-inflammatory drugs are used in the treatment of various infections, either topically (ointments, solutions) or systemic (oral, inhaled, intramuscular and intravenous). Some examples of these steroids are hydrocortisone, dexamethasone, mometasone and betamethasone.

The steroids found in the leaves of sugarcane are: 24-metilcolesta-3,6-diona, 24-etilcolesta-3,6-diona, 24-etilcolesta-22-en-3,6-diona, 6-hidroxi-campest-4-en-3-ona, 6-hidroxistigmast-4-en-3-ona, 6-hidroxistigmasta-4,22-dien-3-ona, 24-metilcolest-4-en-3-ona, 24-etilcolest-4-en-3-ona, 24-etilcolesta-4,22-dien-3-ona, campesterol, stigmasterol and β-sitosterol.

Terpenes Terpenes are a large and diverse class of organic compounds produced by a variety of plants and with vast application in food, cosmetics, pharmaceutical and biotechnology industries. Their structure is characterized by multiple units of the molecule of isoprene (2-methil-butadiene). They can be used as food additive (e.g. Vitamin A), pesticides and repelents, natural rubber, other intermediates (e.g. farnesene), etc. The terpenes isolated from sugarcane wax are arundoin (fernenol methyl ether) and sawamilletin (taraxerol methyl ether), which constitute triterpenes (with six isoprene units).

Flavonoids Just like the terpenes, flavonoids are a vast group of secondary metabolites from plant and fungus pertaining to the class of polyphenols of low molecular weight. Chemically, they have the general structure of a 15-carbon skeleton known as flavone (2-phenyl-1,4-benzopyrone). These components are extensively investigated lately due to their alleged effects on human health, with more than 5000 naturally occurring flavonoids have been described and classified.

A wide range of biological and pharmacological activities have been attributed to these metabolites, including anti-inflammatory, antioxidant and anti-cancer. However, neither the Food and Drug Administration (FDA) nor the European Food Safety Authority (EFSA) has approved any health claim for flavonoids or approved any flavonoids as pharmaceutical drugs. The flavonoids isolated from sugarcane leaves, juice and bagasse are tricin-7-O-neohesperosideo, vitexina, orientina and schaftosideo [81].

Filter cake

Despite currently recycled to the crops as fertilizer, the filter cake can have much more valuable uses.

Cement The clarification process of the sugarcane juice can be done using distinct techniques. Most of the sugar refineries use the sulfitation process, where the sugarcane juice is put in contact with sulfur dioxide gas for conservation and inhibit color formation [180]. Other producers use carbonation for this purpose as it allegedly yields higher quality refined sugar than does the sulfitation [297]. However, opposed to filter cake resulting from sulfitation-based processes, the carbonation-derived filter cake can not be disposed of as fertilizer due to its hazardous effects on the soil. In such case, the filter cake can be sent as input to cement plants [297].

Fertilizer Due to its high phosphorous, potassium, calcium and other nutrients content, the filter cake (from sulfitation) is extensively used as fertilizer — either *in natura* or as a compost, mixed with gypsium, boiler ashes or bagasse and straw. Its application *in natura* is especially appropriate during the winter and dry periods in the South and Southeast regions. Its application as a compost makes it more valuable due to the higher concentration of nutrients, enables its transportation to farther distances [233].

Pirolitic carbon The pyrolisis of the filter cake is also a possibility. It leads to the production of charcoal and bio-oil, which can be respectively used as adsorbent for dye removal from industrial wastewater and biofuel [26]. This technology however is still in the laboratory phase.

Wax Waxes consists of mixtures of lipids and hydrocarbons occurring naturally in plants and animals or synthetized from petroleum [279]. In vegetables they function as barriers for water retention in the plant cells and protection against microorganisms [279]. In the human life, waxes have been used as emulsifiers for coating citric fruits, as waterproofing material for paper and textiles, as polishing fluid and as medicine substract. The extraction and use of wax is an ancient practice and it is still relevant nowadays as, despite the development of synthetic waxes, natural waxes have unique properties that hold their market value.

The production of sugarcane wax from byproducts of sugar refineries has been investigated since the 1950's, with industrial experiences in South Africa, Australia, India and Cuba. In Brazil, a pilot project was started in 2011 but was discontinued in 2014. However, there is currently interest in sugarcane wax for cancer research, anti-aging creams for the cosmetic industry and pharmaceuticals, also for the extraction of its various bio-active compounds. Among the components of sugarcane wax there are tetracosanol (C24OH), hexacosanol (C26OH), octacosanol (C28OH), triacontanol (C30OH), hexacosanal (C25CHO), octacosanal (C27CHO), triacontanal (C29CHO) [81].

Vinasse

It is the most abundant effluent from the distillery.

Biogas The production of biogas from vinasse through anaerobic biodigestion has been investigated for many years [72] but there is no full scale facility operating in Brazil in to present days. Vinasse consists of a fluid appropriate for biodigestion because of its high organic content with average chemical and biochemical oxigen demands above 100 g/L and 50 g/L respectively [136]. Currently, demonstration projects are being conducted by Raizen, Cetrel Bioenergia and Paques do Brasil.

The production of biogas consists on draining the vinasse to a bioreator, where microorganisms or enzymes metabolize the organic matter into methane, water, CO_2 and other gases. Besides the capital cost-effectiveness, a crucial challenge of such technology still lies on the stability of the operation — due to the variable composition of the vinasse — and production of biogas with high (above 96.5%) methane content [89].

Concentrated fertilizer Vinasse can also be dehydrated and concentrated to be commercialized as fertilizer. This use is different from its current usage due to the removal of most of water content, reducing its irrigation potential. This can be done with evaporators or with reverse osmosis systems. Despite this treatment has been attested as feasible in the past [110] it is not explored nowadays.

Carbon dioxide (CO_2)

Carbon dioxide has specific characteristics that makes it a valuable byproduct, especially for the distillery from which it is produced at high purity (99%). It is relatively non-flammable, stable, non-toxic to plants and animals, and can achieve very low temperatures with relatively low energy consumption [290]. It can be used as fire supressant, as preservative, for carbonation of beverages, as solvent, as intermediate for the synthesis of chemicals and biofuels, for enhanced oil recovery and production of algal biofuel [115, 167, 290].

Fire supressant Carbon dioxide has many of the positive attributes as a clean fire extinguishing agent [249]. It is odorless, colorless, corrosion-resistant, non-electrically conductive and extinguishes the fire by reducing the oxygen in the environment [167]. As it is produced in gaseous state from the ethanol recovery equipment [270], it needs to be liquefied to enable its application as fire supressant or to fill propulsion cylinders [270].

Preservative Carbon dioxide can change directly from gaseous to solid state when refrigerated to -78.5 ^oC and pressure is below 5 atm. This property makes it a unique refrigerator fluid as it enable preservation of food, medicines, etc. without wetting them. This is also how dry ice is produced. This application is vastly used and its use in the food industry represents 40 to 50% of CO_2's merchant market [290].

Carbonation of beverages The carbonation of soft drinks represents 20 to 30% of the CO_2 consumer market [290]. It provides the refreshing sense of these beverages while also conserving their integrity until the expiry date [182]. Brazilian legislation requires minimum CO_2 purity of 99.9% [122]. Hence, an additional purification step with a scrubber is essential to remove any odor ingredients that can influence flavor perception [290].

Solvent In the supercritical state [1], CO_2 has proven to be a good solvent for food extraction when comparing with organic solvents . Among the applications, it can be cited decaffeination of coffee and tea, extraction of natural flavors, colors and antioxidants, and separation of fats, lipids and cholesterol from meat, milk, egg and fish [290].

[1] The critical point refers to the temperature and pressure above which a fluid can not be liquefied no matter the pressure applied [290]. In this state, the substance is neither gaseous nor liquid, it is supercritical.

Chemical intermediate Despite its use in the chemical industry is not that substantial, in 2007, nearly 115 million tonnes of CO_2/year were consumed in the chemical industry [290]. The production of urea is the main application, demanding 70 million tonnes of CO_2 per year. Other applications are the synthesis of salicylic acid and methanol. In the production of biofuels, there are investigations in its use for syngas production through catalytic reforming of methane, which are currently in pilot and demonstration stages.

Enhanced oil recovery Enhanced oil recovery (EOR) comprises techniques to increase the throughput of mature or depleted oil fields [256]. The use of CO_2 for such purpose is also known as tertiary oil recovery, since its physico-chemical properties are altered to make it more conducive to extraction [112]. In 2002, the first demonstration project for using ethanol producition-CO_2 for EOR was started in Kansas (USA) [234]. The CO_2 injected in the reservoir reduces the oil viscosity, improving the flow of oil to a production well [290] and expanding the well's productive lifespan.Because a large portion of the injected CO2 remains in place, CO2-EOR is an option for permanently sequestering CO_2 [90]. Some demonstration projects have been conducted in the United States and Norway [90, 147, 234].

Algal biofuel This application comprises the fixation of CO_2 by microalgae used for producing biofuel [234]. While this seem to be a very promissing application due to the potential biofuel yield and carbon capture, ongoing projects are still working on the techno-economic feasibility of the microalgae systems [290].

Fusel oil

The term fusel oil is widely used to denote the mixture of higher alcohols obtained in various stages of the alcohol purification process. Isoamyl and isobutyl alcohols are its main constituents, with n-amyl, n-butyl and isopropanol alcohols being produced in minor amounts. Also in the fusel oil are ethyl, propyl, butyl, hexyl, heptyl and other alcohols, in addition to acids, esters and aldehydes [138].

Hence, in order to be reused, the fusel oil needs to be separated into its main components [21]. This is done through further distillation, decanting and stripping [138]. There are only a few studies exploring the use of fusel oil. Its commercial application is mainly to extract isoamylic and isobutyl alcohols, while the residues of such process can be used as coalescer in the manufacture of paints and varnishers [138].

Animal feed Due to its high proteic content, the main application of used yeast is for the production of animal feed [221]. It can be either mixed to bagasse or sugarcane tip which provide volume and fiber to the mixture. For this purpose, the used yeast has to be previously dried [72]. The industrial process for producing dry yeast consists of pumping of the bottom yeast from the first tank and from the centrifuge to the thermolizer, where the wine is removed to be reused. Thereafter, the yeast is concentrated in a vaporizer and dehydrated with a drier. After drying the yeast is packed [44].

Cement substitute Some studies have shown that the ash from the burning of bagasse is a viable residue for partial substitution of cement [71, 187]. Its chemical composition obeys the minimum required by ABNT NBR 12.653 (2001), and the pozzolanic activity is above the minimum required by ABNT NBR 15.895 (2010). The partial replacement of cement by light ash from sugarcane bagasse in the production of pavers is feasible at 5%, making it possible to use lightweight applications such as pedestrian traffic [187].

Soil conditioner Soil conditioner is a substance that can be added to soil to change the soil properties [2][272]. The boiler ashes are rich in potassium, so that it can be used to replenish and maintain soil nutrients.

[2] A soil conditioner is said of the substance that is deemed as beneficial for plant life but that neither provides nutrients (as fertilizers do), nor delivers biology to the soil (as inoculants do) [272].

Appendix C

Scientific production

Scientific papers in journals

1. Santos, V. E. N., & Magrini, A. (2018). Biorefining and industrial symbiosis: A proposal for regional development in Brazil. Journal of Cleaner Production, 177, 19–33. https://doi.org/10.1016/j.jclepro.2017.12.107

2. Santos, V. E. N., Ely, R. N., Szklo, A. S., & Magrini, A. (2016). Chemicals, electricity and fuels from biorefineries processing Brazil's sugarcane bagasse: Production recipes and minimum selling prices. Renewable and Sustainable Energy Reviews, 53, 1443–1458. https://doi.org/10.1016/j.rser.2015.09.069

Scientific papers in conference proceedings

1. Santos, V., Szklo, A., & Magrini, A. (2014). Building a "bio-perspective" from petroleum revenues: a pathway through Bioplatforms' Oriented Biofineries in Rio de Janeiro State, Brazil. In D. Buchan (Ed.), World Petroleum Congress Proceedings - Volume 2 (pp. 1344–1352). Moscow: Energy Institute. https://doi.org/0852936982

Book chapter

1. Veiga, L. B. E., & Santos, V. E. N. (2018). Planejando a Criação de Parques Eco-Industriais e Simbioses Industriais. In A. Magrini & L. B. E. Veiga (Eds.), Fechando o ciclo de materiais: desafios no contexto da Economia Circular (In press). Rio de Janeiro: Synergia.

Other productions

1. Mulrow, J., & Santos, V. (2017). Moving the Circular Economy Beyond Alchemy. Retrieved from https://discardstudies.com/2017/11/13/moving-the-circular-economy-beyond-alchemy/

2. Santos, V. E. N., Nikolic, I., & Ramirez, A. (2017). Exploring the potential for Industrial Symbiosis in Brazilian small scale sugarcane industry using Agent Based Modelling. In Book of Abstracts of ISIE-ISSST 2017: Science in Support of Sustainable and Resilient Communities. Chicago, IL, USA.

3. Santos, V. E. N., & Magrini, A. (2015). Proposal of Industrial Symbiosis as the Productive Arrangement of a Biorefinery in Brazil. In Book of Abstracts of ISIE International Conference 2015.