A Context-specific Conceptual Process Design for the Jamaican Sugar Industry

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by

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Abstract

Biorefineries are considered an integral part in the transition to sustainable bio-based economies as they can convert renewable biological resources into various bio-based products, while co-products are recycled and energy is produced out of the residuals. In this thesis, it is suggested to use the biorefinery concept to revive the sugar industry of Jamaica, where currently only raw sugar is produced. For this, the development of a conceptual process design and the feasibility of the implementation is studied as the entire chain of utilizing biomass is influenced by both technical, environmental, social and economic aspects. With the Technological Innovation System (TIS) framework, the information obtained during the fieldwork about how (new) technologies function in the Jamaican agricultural industry is translated into context-specific design constraints. The design constraints are used in the development of the context-specific conceptual process design for the Jamaican sugar industry. Three scenarios of the proposed design including the material balances and financial viability are discussed. The "status-quo" scenario predicts the bankruptcy of some of the sugar factories due to the reduced possibility to sell raw sugar, which will also leave farmers without income. The "technical-ideal" scenario was found to fail due to the unrealistic assumptions that all the products can be sold, that the farming yields can be improved, and that the Jamaican sugar sector can be seen as one. In the "most-realistic" scenario, it is considered that the energy generation from bagasse covers the energy demand for the processes and that the amount of plantation white sugar, anhydrous bio-ethanol and bio-pellets annually produced from 30,000 hectares of sugarcane land equal 100,000 tonnes, 51 million liters, and 80,600 tonnes, respectively. It is suggested that in this "most-realistic" scenario, the Jamaican sugar industry is revived and that the establishment of the sustainable bio-based economy is supported if the financial viability of the project and the inclusiveness of the various actors remain considered.

Preface

This research has been carried out as part of the degree of Master of Science in Chemical Engineering at the Delft University of Technology. Chemical Engineering master students usually conduct their thesis at the Department of Chemical Engineering. However, I decided to join the section Biotechnology & Society of the Department of Biotechnology. The Biotechnology & Society section performs leading research on understanding societal and sustainability aspects of biotechnology and translates this research into responsible innovation and communication of biotechnology for sustainable development [1].

The reason I joined this research group is my interest in the interface between the development of technology itself and the feasibility of the implementation of the technology in society. I found this combination of applied and social science in the Inclusive Bio-based Innovations (IBIS) project supervised by dr. Lotte Asveld and dr. Zoë Robaey at the Biotechnology & Society section of the Delft University of Technology [2]. Within the IBIS project, I have worked on the development of the Jamaican sugar industry with the aim to support the sustainable bio-based economy in Jamaica.

In this thesis, I propose a context-specific conceptual process design for the Jamaican sugar industry taking into account both technical, societal, economical and sustainability aspects. This thesis contributes to an enhanced understanding on how the development of technical processes can be influenced by the context. The results of this research are communicated to the partners of the IBIS project and to interested parties in the Jamaican sugar sector.

By conducting this research, I was able to gain experience on the development of a technical process in the society of a developing country. I discovered the tremendous influence of the context on engineering practices and decisions. Besides that, I learned how to execute a socio-technical project and how to make appropriate choices based on reasoning and reflection. I would like to thank dr. Lotte Asveld for being my supervisor and for giving me the opportunity to work on this thesis. Also, I am very grateful for the time the thesis committee, dr. Lotte Asveld, Prof. dr. ir. André B. de Haan and dr. ir. Michiel Makkee, spent on reading my thesis and for attending my defense as my thesis could not be finalized without them. Above all, I would like to express my gratitude to my daily supervisor dr. Zoë Robaey for her encouraging and inspiring support, patient guidance and constructive feedback. Moreover, I would like to thank the people from the Biotechnology & Society section and the partners of the IBIS project, who were willing to support me by sharing their knowledge and experiences. Also, their feedback and suggestions have been much appreciated. It was an instructive and joyful experience for me to work on this project and I hope that this will be visible when reading this thesis.

Sara Francke
Delft, September 2018

Nomenclature

Abbreviations

AIJCFA	All-Island Jamaica Cane Farmers' Association
B.V.	Besloten vennootschap (Dutch)
BFD	Block flow diagram
BTS	Biotechnology & Society
CAPEX	Capital expenditures
C_2H_5OH	Ethanol
$C_6H_{12}O_6$	Dextrose
CO_2	Carbon dioxide
E10	Transportation fuel consisting of 90% gasoline and 10% anhydrous bio-ethanol
HCV	Higher calorific value
i	Discount rate
IBIS	Inclusive Bio-based Innovations
JCPS	Jamaica Cane Products Sales Limited
JPS	Jamaica Public Service Company Limited
LCV	Lower calorific value
n	Number of time periods
NPV	Net present value
OPEX	Operational expenditures
PFD	Process flow diagram
P&ID	Piping and instrumentation diagram
PWS	Plantation white sugar
SIA	Sugar Industry Authorities
SIARD	Sugar Industry Authority Research and Development Division
SIRI	Sugar Industry Research Institute
SMCJ	Sugar Manufacturing Corporation of Jamaica
TIS	Technological Innovation System
TPC	Total production costs

Units

g	gram
ha	hectare
J	joule
kWh	kilo watt hour
l	liter
m	meter
t	tonne
tb	tonne of bagasse
tc	tonne of sugarcane
tp	tonne of bio-pellets
ts	tonne of sugar
y	year

Contents

1 Introduction

1.1. Sustainable Bio-based Economy

Alternative products and processes are necessary worldwide in order to reduce the dependence on fossil fuels, enhance energy security, support sustainability and mitigate climate change [3, 4]. The alternative to fossil resources for the production of chemicals is mainly dependent on biomass, as the other renewable alternatives (i.a. wind, solar, hydro, geothermal) cannot act as a carbon source [5–8]. Biorefineries are considered an integral part to convert the renewable biological resources and establish the bio-based economy [9–13]. The biorefinery concept aims to obtain maximum value out of the biomass feedstock, this is done by converting the biomass into various bio-based products through jointly applied conversion technologies, by recycling co-products, and by producing heat and power out of the residuals [12, 14–17]. In addition, there is an aim to obtain zero net carbon emissions and zero net waste, and to use a minimum amount of water and energy to achieve sustainability and economic feasibility. In other words, the key principles of the biorefinery concept are diversification and integration.

Based on the aims of the biorefinery concepts it looks promising to transfer existing, successful biorefinery concepts from their country of origin to countries where these are not yet applied. However, transferring existing and proven technology from one country to another is not just a simple cut-and-paste job. The entire chain of utilizing biomass to replace fossil fuels is much more complex than the technical feasibility alone. This is due to the tremendous influence of the widely differing environmental, social and economic aspects for the various biomass feedstocks and processes [18–21]. In March 2018, a newspaper in the Netherlands reported the failure of a large bio-ethanol project in Sierra Leone [22]. What should have been a project to revive the economy, establish a developed agriculture and improve the livelihood of locals, turned out to be a complete disaster where the people were left poorer than before. Another example showing the complexity of using biomass as replacement for fossil fuels is related to the Renewable Energy Directive of the European Parliament. In this directive, it is endorsed that the European Union is mandatory to satisfy at least 20% of its total energy from renewable resources and at least 10% of their transport fuels from renewable resources by 2020 [23]. This seems like a noble endeavour, however the reality turns out to be different. In December 2017, The Guardian reported an article written by several professors about the flaw in the Renewable Energy Directive [24]. In this article, it is argued that the flaw allows fuel from felled trees to be qualified as renewable energy, which results in the acceleration of carbon dioxide emissions and devastation of the forest. In addition, The DailyMail reported in February 2017, that in the United Kingdom hundreds of millions of pounds of subsidy were spent on wood pellets that where imported from the United States, which actually did more damage to the environment just by the transport [25].

These examples indicate that the performance of a sustainable bio-based economy is not only dependent on the technical feasibility of the biorefinery concept, but also on the adaptability and flexibility of the social system with regard to the (new) technologies. The interplay between technology and the social system is addressed in this thesis for the Jamaican sugar industry. Why the Jamaican sugar industry is chosen and what is actually addressed in this thesis is explained in the following sections.

1.2. Thesis and IBIS Project

The research described in this thesis is part of the Inclusive Bio-based Innovations (IBIS) project from the Biotechnology & Society (BTS) section at the Delft University of Technology. The IBIS project deals with the interplay between the various stakeholders in a bio-based value chain [2]. The project description explains that the aim of the IBIS project is to have a model describing how the bio-based value chain can be designed to secure sustainable supply of bio-resources and improve agricultural management. Special attention goes out to align farmers' values, interests, knowledge and concerns with the socio-economic and technical requirements of other partners in the chain. The IBIS project contains five case studies in the United States of America, Brazil, South Africa, the Netherlands and in Jamaica.

This thesis complements the research executed by the IBIS project for the Jamaican case. Jamaica is highly dependent on the import of all kinds of products including food, feed, consumer goods, capital goods, industrial supplies, and fuels [26]. However at the same time, Jamaica is called *"The Land of Wood and Water"*, which can be freely interpreted as *"The Land of Biomass and Water"*. In this context, one might wonder if it is possible for Jamaica to establish a sustainable bio-based economy and strive towards self-sufficiency based on biomass. This can make the dependence on the import of food, feed and energy no longer a necessity and it can result in, for example, job creation and economic growth that strengthen the socio-economic values. To enable this self-sufficient and sustainable bio-based economy in Jamaica tremendous effort should be made on improving existent technologies and implementing new technologies as currently, the agricultural sector is low-tech and not very efficient. The technological improvements and changes must be executed while taking into account the social system in order to ensure the suitability and feasibility of the technology in the context and to prevent unexpected failure such as in the Sierra Leone case described in the previous section.

1.3. Research Question

The focus of this thesis is at the interface between the development of a technical process and the feasibility of the technical process in the context of the agricultural industry of Jamaica. By emphasizing whether the technical process is suitable in the context, it can be better assessed whether the design can actually be successfully implemented. The Jamaican sugar industry is chosen as the area of interest. The sugar industry is one of the largest players in the agricultural industry of Jamaica and is currently dealing with many changes challenging the viability of the industry. In this thesis, a context-specific conceptual process design for the Jamaican sugar industry is developed with the aim to revive the Jamaican sugar industry and to support the establishment of a self-sufficient sustainable bio-based economy in Jamaica. The objective of supporting the sustainable bio-based economy is based on the research focus of the IBIS project and the BTS section. Moreover, it is also due to my own motivation to contribute to the sustainability of life on earth. The revitalization of the Jamaican sugar industry within the establishment of the sustainable bio-based economy by improving existent technologies and implementing new technologies results in the research questions of this thesis:

How to develop a context-specific conceptual process design for the Jamaican sugar industry in order to support the sustainable bio-based economy?

The main research question is divided into the following subquestions:

1. What is the current state of the sugar industry in Jamaica?
2. Which context related constraints for the Jamaican sugar industry can be defined?
3. What is the effect of the constraints on the design choices?
4. What is the flow diagram of the process design going to look like?
5. Is the context-specific conceptual process design financially viable?

1.4. Methodology

The subquestions belonging to the research question as defined in the previous section are elaborated upon in consecutive chapters in this thesis. The first question about the current state of the Jamaican sugar industry is investigated by carrying out an open online search on Jamaica in general and the sugar industry in Jamaica in more detail. In addition, a field trip to Jamaica was executed to gain more knowledge about the current state of the sugar industry. During this fieldwork several open discussions were carried out with people involved in the agricultural sector in Jamaica. The information gathered from the online search and obtained during the fieldwork are included in chapter 2 and chapter 3, respectively.

The second subquestion requires the translation of the findings and observations regarding the agricultural industry into design constraints that are context-specific for the Jamaican sugar industry. The Technological Innovation System (TIS) framework is the method used to convert the information received during the field trip into the context-specific design constraints. In addition, the supply chain of the Jamaican sugar sector is constructed as part of the fieldwork analysis. An explanation of the TIS framework and the fieldwork analysis using the TIS framework are also included in chapter 3.

The combination of the defined context-specific design constraints and the supply chain displays the boundaries within which the conceptual process design for the sugar industry can be developed. Within these boundaries, the choices made to develop the process design are defined as requested by the third subquestion. Chapter 4 explains in detail the relation between the five design choices and the defined design constraints. The five design choices result in the context-specific conceptual process design for the Jamaican sugar industry.

The fourth and the fifth subquestions are about the flow diagram and the financial viability of the proposed context-specific conceptual process design. For this, data is gathered from the Jamaican sugar industry and from the literature as not all data could be obtained from the Jamaican sugar industry. This was due to the fact that the proposed design includes processes which are not currently in operation in the Jamaican sugar industry and also because of insufficient data gathering and communication in the Jamaican sugar sector. The data from the Jamaican sugar industry and the data extracted from literature are included in chapter 5.

To further engineer the proposed context-specific conceptual process design the material balances were studied in chapter 6. With the mass and energy balances of the block flow diagram more insight is given in what the process design is going to look like in practice as requested by the fourth subquestion. It was found that the domestic demand for sugar and bio-ethanol in Jamaica could not be achieved when the processes in the proposed process design were operated with the current processing yields. Therefore, the influences of the yields of the process variables on the material balances were investigated. Chapter 6 concludes with an overview of the potential yields of the process variables that are suggested feasible in the context.

In chapter 7, the financial viability of the proposed context-specific conceptual process design is assessed. For this, the sales revenues, the market prices, the market volumes, the operational costs, the capital investments and the total production costs are described for the products and processes as proposed in the conceptual process design. With the overview of the cash inflow, cash outflow and total initial investments cost, the net present value is determined for the production of anhydrous bio-ethanol and bio-pellets in the Jamaican sugar industry.

All the information obtained in the previous chapters is combined in chapter 8, which entails a discussion on three scenarios of the proposed context-specific conceptual design for the Jamaican sugar industry. The first scenario describes the status quo of the sugar industry in Jamaica. The second scenario gives the technically ideal option. The third scenario shows the most realistic option as considered in this thesis. For all scenarios the design choices are specified and the possible implications of the design in the context are given.

2
About Jamaica

To have a solid background on which decisions can be made on how to develop the context-specific conceptual process design for the Jamaican sugar industry, information about Jamaica in general and the sugar industry in more detail is given in this chapter. Topics discussed are demographics, history, politics and economics, climate, energy and the sugar sector itself.

"Out of Many, One People" and *"The Land of Wood and Water"*, two sayings which are proudly presented by the Jamaican people and reflect well the diverse and colourful island. Jamaica is the fourth largest island in the Caribbean and is located about 145 kilometer south of Cuba and 191 kilometer west of Haiti. The island has an area of almost 11,000 square kilometers and is divided into 14 parishes. Kingston is the capital and largest city of Jamaica located south east on the island, see Figure 2.1. Around 1 million of the 2.7 million inhabitants in Jamaica live in Kingston and another 2 million Jamaicans live abroad [27–30].

Figure 2.1: Google Maps Satellite, March 2018.

2.1. History

The history of Jamaica is quite vibrant and it still has an influence on the way of thinking and doing of the current inhabitants. In order to understand the context of the sugar industry, it is of great importance to know the general history of the island.

The indigenous inhabitants of Jamaica were Arawaks. They led quiet and peaceful lives based on agriculture and fishery until Christopher Columbus discovered the island in 1494. After the discovery, the Spaniards conquered the land. The slaughtering in combination with the European diseases, to which the Arawaks had little to no resistance, led to the complete extinction of the Arawaks. Therefore, the Spanish introduced African slaves, who had to work on the land replacing the Arawaks. The island did not flourish under the Spanish rule and mainly served as a supply base to help in conquering the American mainland. In May 1655, the country fell under English rule causing the Spaniards to release their slaves and flee to Cuba themselves. The freed slaves fled into the mountains of Jamaica and are still known as the Maroons. During the English rule, the agricultural industry grew rapidly and sugar and rum became the main export products of Jamaica. The English continued the use of African slaves on the plantations and even increased the trading of slaves from Africa to the West Indies. However, frequent slave rebellions organized by trapped slaves, the Maroons and fled slaves with the support from humanitarian groups led to the abolition of slavery in 1808 and full emancipation in 1838. Despite some hurdles in the post-slavery days and during the worldwide economic depression in the 1930s, the island developed into a sovereign state. In August 1962, Jamaica was granted its independence from England and became a member of the Commonwealth of Nations. Remainders of the English colonization are the official English language, a military force based on the British military model, and driving on the left [27, 28].

2.2. Politics and Economics

This section briefly explains the political situation in Jamaica and indicates some issues related to the politics and economics. This information gives insight in the play field of the sugar industry and is therefore important to know to be able to develop the context-specific conceptual process design.

Since the independence of England in 1962, Jamaica has been an unitary parliamentary constitutional monarchy. The parliament consists of Her Majesty the Queen, represented by the Governor-General, and two legislative Houses, a nominated Senate and an elected House of Representatives. Jamaica has a two-party system, with the power alternating between the People's National Party and the Jamaica Labour Party of which the latter is in charge since 2016 [28, 30]. According to the Worldbank, Jamaica is one of the slowest growing developing countries in the world and it is facing high public debt and a weakened economy that is mainly dependent on external factors. In 2016, 14.5% of the population lived below the national poverty line of US$ 1.90 a day, which indicates the minimum level of consumption needed to maintain the lowest acceptable standard of living [29–31]. In the United Nations Development Programme for Jamaica special attention goes out on how to tackle the poverty [32]. Another hurdle for the Government of Jamaica is the large unemployment rate. Since 2010, the unemployment rate fluctuates around 12% [29, 30]. To compare, the unemployment rate in The Netherlands averaged 5.4% from 2003 until May 2018 [33]. Besides poverty and unemployment, Jamaica is afflicted by corruption and crime. A remarkable fact is that in 1962, the year of the independence, the murder rate in Jamaica was one of the lowest in the world, while in 2009 the country was having the highest murder rate worldwide. Jamaica is still facing high levels of crime and violence, especially in the larger cities [34].

The Jamaican sugar industry has to be revitalised within this play field of corruption, crime, poverty and unemployment. Besides this, the sugar industry is struggling to survive the fall away of the preferential treatment. Since 1975, Jamaica was able to enjoy the preferential treatment for sugar prices and the guaranteed sugar quota from the European Union. However, in 2009 the difference between this guaranteed market and the global market prices was reduced and in 2017 the preferential treatment completely ended. During the preferential treatment period, hardly any improvements were made in the farming practices and industrial processes in the Jamaican sugar industry. By that time it did not matter that their processes were not globally competitive as they received a fixed price for a fixed quantity of sugar. However, due to the fall away of the preferential treatment the Jamaican sugar industry has to trade on the world market and therefore should be able to produce globally competitive if they want to survive [meeting 2, Table 3.1].

2.3. Climate

As people we are able to control the growth of agricultural crops to a large extent, but agricultural crops are still a product of mother nature and thereby highly dependent on the climate. Regarding the sugar industry, the climate plays a major role in the quality and quantity of sugarcane that can be produced and should therefore be taken into account when developing the context-specific conceptual process design.

Jamaica has a tropical climate, this means that the average temperature is above 18°C and there are periods of intensive rain, annually [28]. Unfortunately, Jamaica is highly affected by climate change as can be seen by the increasing occurrence of natural disasters in the past year. These disasters range from floods related to inclement weather, tropical depressions and storms, severe hurricanes, to droughts and landslides [35]. Losses in the ecosystem, national economy and livelihood are only some examples of the devastating consequences. For the sugar industry specifically wet seasons result in a low sugar content in the sugarcane and in difficulties during harvesting due to the muddy land, while during dry seasons the sugarcane hardly grows. The Government of Jamaica has developed a climate change adaption framework and it started a project to address climate change and reduce the risk on climate related disasters together with the European Union and United Nations Environmental Program [36–38].

The tropical climate also results in a rich and diverse ecosystem in the mountains, along the coast and in the rainforest. There are several protected areas in Jamaica to preserve the variety of flora and fauna; Cockpit Country, Hellshire Hills, Blue and the John Crow Mountains National Park, and Portland Bight Protected Area [39]. In this *"Land of Wood and Water"*, it is almost possible to observe the plants blossom and grow, which explains the major position of the agricultural industry. The main agricultural export products are yam, ackee, raw sugar, banana, coffee and rum. About 17% of the working people is employed in the agricultural sector. Besides the agricultural industry, the main industries in Jamaica are tourism and mining of bauxite and alumina [29, 30].

2.4. Energy

In the beginning of this thesis it was stated that biomass can be an alternative for fossil fuels. Only 6% of the energy used in Jamaica in 2016 was generated from renewable resources, as shown in Figure 2.2. This indicates that fossil fuels do still represent a major part of the imported products in Jamaica. However, the conversion of biomass into biofuels and chemicals creates major opportunities for the Jamaican agricultural industry to step into.

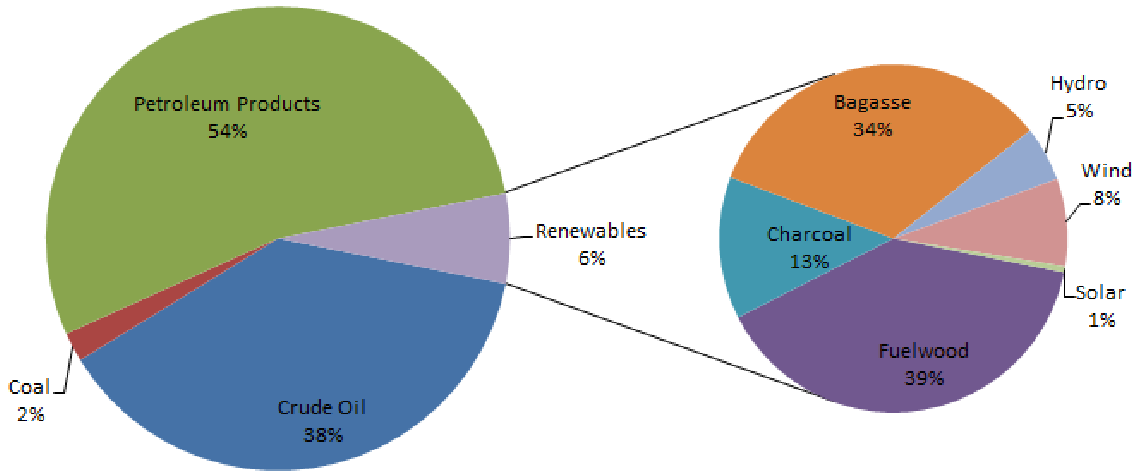

Figure 2.2: Energy balance of Jamaica in 2016, Ministry of Science Energy & Technology [40].

In 2009, Jamaica's National Energy Policy 2009-2030 came into effect which was designed to ensure that by 2030 Jamaica achieves: "A modern, efficient, diversified and environmentally sustainable energy sector providing affordable and accessible energy supplies with long-term energy security and supported by informed public behaviour on energy issues and an appropriate policy, regulatory and institutional framework" [41]. The main priorities of this policy are securing energy supply, modernizing the energy infrastructure, developing of renewable energy sources, energy conservation and efficiency, developing of a regulatory framework, and enabling role models for energy management. In this national energy policy a target is set for renewable energy and the percentage of diversification of the energy supply as a reaction to the spiralling cost of oil prices and the increasing demand for fossil fuels. The target requires that by 2030, 20% of Jamaica's energy mix should be generated from renewable resources.

The National Renewable Energy Policy 2009-2030 was developed to be able to meet this target of 20% of renewable resources [42]. The primary focus of this renewable policy is on the deployment of wind, solar and hydro technologies, the emerging potential and deployment of biomass and biofuels, the development of energy-from-waste initiatives, and exploratory work on ocean energy. This policy emphasizes that in a bio-based economy, biomass should not only be used for food and feed, but it can also be converted to energy, materials and chemicals. Energy generation from biomass is proposed to be done by co-generation from bagasse, by bio-ethanol production, by burning of fuelwood and charcoal, and through anaerobic decomposition of organic waste. The Jamaican sugar industry can respond to this emerging potential of biomass utilisation by the co-generation from bagasse and the bio-ethanol production.

2.5. Sugar Sector

The previous sections entailed some information on the demographics, history, politics and economics, climate, and energy of Jamaica, which contribute to a better understanding of the Jamaican sugar industry. This section provides more detailed information of the Jamaican sugar industry, which is amongst others obtained from the Sugar Industry Authorities of Jamaica (meeting 2, Table 3.1) [43], the Jamaica Sugar Industry Research Institute [44], the All-Island Jamaica Cane Farmers' Association (meeting 3 & 8, Table 3.1) [45], a report about the renewable energy potential in Jamaica from 2005 [46], a report of the sugar industry enquire commission from 2010 [47] and the Jamaica sugar annual report from 2017 [48].

In Jamaica there are approximately 56,700 hectares of sugarcane land [49]. From this potential amount of land about 30,000 hectares were actually harvested in the harvest season 2016-2017 [48]. Of this sugarcane land about half of the hectares is owned by the estates and half is owned by private and subsistence farmers [46]. In general, the private and subsistence farmers do have small farms of one to several hectares [meeting 2, 4, 5 & 8, Table 3.1]. Harvesting normally takes place between November and April, however it can be earlier or later depending on the weather. The sugar factories and farmers have to work in close collaboration to match the harvest to the capacity of the factory as sugarcane has to be processed within 3 days to avoid major deterioration [meeting 2, 4, 5 & 8, Table 3.1]. Sugarcane has to be replanted every seven years and this requires a high investment. However, if the sugarcane is planted the variable costs are relatively low. A disadvantage of this seven years cycle is that it reduces the flexibility of the farmers with regards to planting other crops when sugar prices are low or if other crops are expected to be more promising [50]. The farmers are paid for their sugarcane by the estate on a ratio of 62:38, which means that 62% of the income from the raw sugar is going to the farmers and 38% is going to the factories [49].

The harvest yield in the Jamaican sugar industry is varying between 45-65 tonnes of sugarcane per hectare [meeting 2, 4, 5 & 8, Table 3.1], while in literature it is reported that other countries can achieve yields around 75-90 tonnes of sugarcane per hectare [51–55]. In the harvest season 2016/2017, about 1.8 million tonnes of sugarcane were supplied to the 5 operating sugar factories in Jamaica (Golden Grove, Monymusk, Frome, Appleton and Worthy Park) [48] [meeting 2, 4 & 8, Table 3.1] . This sugarcane was processed into about 140,000 tonnes of raw sugar, which gives a yield of 0.08 tonnes of raw sugar per tonne of sugarcane and of 4.6 tonnes of raw sugar per hectare [48]. Those yields are quite low in comparison to the performances of the Jamaican sugar industry in the years 1999-2003, where the average sugar yield was about 5.3 tonnes of sugar per hectare [46]. Also, in literature higher yields are reported of 0.10-0.12 tonnes of sugar per tonne of sugarcane [56] and 7.3-13.1 tonnes of sugar per hectare [51]. In another article, a range of 0.04-0.16 tonnes of sugar per tonne of sugarcane was observed for 30 genetic stocks at different stages of growth [57].

From the produced 140,000 tonnes of raw sugar in 2016/2017, about 80,000 tonnes were exported with a value of about US$ 1.5 million [48, 58]. The remaining raw sugar was used to supply the domestic market, which demands between 50,000-60,000 tonnes of raw sugar [46–48]. In addition, the alcoholic beverage industry consumes about 100,000 tonnes of molasses [48]. Jamaica does not produce refined sugar and therefore needs to import the domestic demand. In 2016/2017, the country imported 70,000 tonnes of refined sugar valued at about US$ 28 million [48, 59, 60].

In the report of the sugar industry enquire commission (2010), a raw sugar production between 200,000-300,000 tonnes per year is suggested to be essential for the viability of the Jamaican sugar industry

[47]. In this report it is also argued that this amount of raw sugar is within the total potential capacity of the Jamaican sugar industry. In the report about the renewable energy potential in Jamaica (2005) and the report from the sugar industry enquire commission (2010), it is mentioned that the production of the Jamaican sugar industry has been in a state of decline and uncertainty [46, 47]. This is shown by the fact that in 1980 more than 250,000 tonnes of raw sugar were produced, which makes a clear contrast to the 140,0000 tonnes of raw sugar produced nowadays [46]. Section 2.2 explains that the actors in the Jamaican sugar industry have to deal with the corruption, crime, poverty and unemployment present in Jamaican. Besides this, there has to be dealt with the disabling of the sugar industry by expired price agreements, which results in the fact that the Jamaican sugar sector has to compete with more efficient sugar producing countries. This is quite challenging for an industry which currently operates below the global competition level as was shown with the relative low sugarcane and sugar yield. Another important uncertainty factor in the Jamaican sugar industry is the dependence on the climate as the sugarcane yield, the sugar content in the sugarcane, as well as harvesting of the sugarcane are all highly affected by the state of the weather.

One of Jamaica's strategies to keep a share in the world sugar market is the privatization of the sugar sector [47, 61]. The government of Jamaica, represented by the Sugar Industry Authorities (SIA) since 1970, is co-owner of several factories, but wants to lay down all responsibility with regards to operations. Instead of having a share in the sugar factories, SIA aims to be a regulator only and wants to focus on regulatory policies creating the fair rules regarding quality, planning, research & development and marketing [43]. The private sector, which include both farmers and sugar factories can make agreements together that follow the fair rules set by SIA. A part of SIA is the Sugar Industry Authority Research and Development Division (SIARD), also called the Sugar Industry Research Institute (SIRI). SIARD/SIRI has the vision to develop a modern sugar industry geared to build rural economic growth and they also provide extension officers, who support the farmers and sugar factories by improving their practices [44]. In line with the privatization strategy it is questioned whether SIARD/SIRI should be turned into a private research company like CTC in Brazil, Cenicaña in Colombia and Cengicaña in Guatemala [49, 61]. Another actor in the sugar sector is the Jamaica Cane Products Sales Limited (JCPS). JCPS is a non-profit corporation established in 1986, it is equally owned by the Sugar Manufacturing Corporation of Jamaica (SMCJ) and the All-Island Jamaica Cane Farmers' Association (AIJCFA) [62]. The JCPS is authorized by SIA as the marketing agent for domestically produced raw sugar and molasses, and also for imported refined sugar.

Despite several attempts to improve the efficiency of farming and industrial practices, reduce production costs, diversify the market in the sugar sector, and attract investors who stimulation the privatization the Jamaican sugar industry is low-tech and far from being globally competitive [meeting 2, 3, 4, 5 & 8, Table 3.1].

3
Fieldwork Analysis

This chapter starts with some general information about the field trip to Jamaica, which was executed as part of this thesis. The second section explains the Technological Innovation System (TIS) framework, which is the method that is used to make sense of the information received during the field trip. The fieldwork analysis using the TIS framework has resulted in the construction of the supply chain of the Jamaican sugar sector and in the determination of the design constraints related to the Jamaican sugar industry, which are described in the third section of this chapter.

3.1. Fieldwork

3.1.1. Description and Method

The field trip to Jamaica has been carried out from February 13th to 22nd in 2018 by dr. Lotte Asveld, dr. Zoë Robaey, and myself. The fieldwork was executed as part of the IBIS project and as part of the research described in this thesis. The aim of the field trip was to gain more knowledge about existing bio-based value chains, farming practices, the current technical status of the agricultural industry and the social system related to the agricultural sector. To gain this knowledge and understanding about the context of the agricultural sector, open discussions with various people were carried out and field visits were made. The information obtained during the meetings and visits is used in this thesis to understand the context of the Jamaican sugar sector.

Table 3.1 lists the meetings carried out during the fieldwork including the persons met, the locations of the meetings and the main topics of the conversations. We had open discussion with people from the Sugar Industry Authority, the University of the West Indies, the All-Island Jamaica Cane Farmers' Association, and the College for Agriculture Science and Education. In addition, we have visited and had open discussions with the people from Old Tavern Coffee Estate, Worthy Park Sugar Estate, New Horizon Skill Training Facility, Jeffrey Town Farmers' Association, Monymusk Sugar Estate (only visit, no discussion), and the Agricultural Research and Innovation Facility of the University of the West Indies. Also, we were present at the general meeting of the All-Island Jamaica Cane Farmers' Association, where the farmer representatives of the different parishes discussed their activities and concerns regarding the sugarcane harvest in their parish. In this thesis, there is referred to the open discussions and visits by using the reference numbers given in Table 3.1. Appendix A contains some photos and extra information of the visits to Worthy Park Sugar Estate [meeting 4, Table 3.1] and Monymusk Sugar Estate [meeting 9, Table 3.1]. The photos in Appendix A show amongst others the sugarcane land, sugar content analysis, unloading and storage of sugarcane, sugarcane processing and sugar packaging.

3.1.2. Challenges

It turned out to be hard to schedule meetings in advance due to a lack of information and communication. Therefore, the meetings were arranged via partners from the IBIS project while we were already in Jamaica. It should be noted that even though the schedule in the end was diverse and convenient, arranging meetings on the spot imposes limitations. For example, it was sometimes impossible to prepare an interview as it was not exactly known in advance who we were about to meet. This was also difficult for the people we met as they did not exactly know about our work and the purpose of the meeting. This is why we rather speak of open discussions instead of interviews. Also, the meetings that were scheduled were sometimes canceled a few hours before. Moreover, we experienced that recording the meeting was not always desirable. However, all the persons we met, agreed that we were taking notes.

Table 3.1: List of the meetings carried out during the fieldwork in Jamaica including the persons met, the locations of the meetings and the main topics of the conversations.

Date		*Reference Number*
2018-02-13	**University of the West Indies, Mona Campus, Kingston** Dr. Arlene Bailey (Senior Research Fellow at SALISES, Associate Dean at Faculty of Social Sciences), and Prof. dr. Marcia Roye (Professor of Molecular Virology, Associate Dean at Faculty of Science and Technology) - The effect of research outcomes in best practices for farmers and opportunities for a bio-based economy	1
2018-02-13	**Sugar Industry Authority, Kingston** Philip Henriques (Chairman of Sugar Industry Authority and of Civil Aviation Authority) - Regulating and revitalizing the sugar industry	2
2018-02-14	**Old Tavern Coffee Estate, Blue Mountains** David Twyman (Owner) - Growing coffee beans and process them into coffee	Not included
2018-02-15	**All-Island Jamaica Cane Farmers' Association, Kingston** Allan Rickards (Chairman), and Nigel Myrie (Secretary/Manager) - Farmers' representative meeting	3
2018-02-15	**Worthy Park Sugar Estate, St Catherine** Robert G.F. Clarke (Managing Director) *Worthy Park Sugar Estate is the most efficient sugar factory in Jamaica since 1968.* *They process 210.000 tonnes of sugarcane annually to produce raw sugar and rum.* - Harvesting of sugarcane, processing of sugarcane into raw sugar, and production of rum	4
2018-02-16	**College for Agriculture Science and Education, Portland** Dr. Derrick Deslandes (President), and Markland Murphy (Co-opted member) - Integrating science and technology in the agricultural sector by business model development	5
2018-02-20	**New Horizon Skill Training Facility, Spanish Town** Michael K. Barnett (Executive Director, BioSystems Designer) - Teaching young people adequate technical skills and professional development to be resilient in life	6
2018-02-20	**Jeffrey Town Farmers' Association, St Mary** Ivy Gordon (Company Secretary & Financial Controller), and Doneille Derrett (Trainee) - Development of various kinds of flour to tackle issues of food security and to develop the livelihood in one of the poorest communities of Jamaica	7
2018-02-21	**All-Island Jamaica Cane Farmers' Association General Meeting, Kingston** - Current situation with regard to the performances of the farmers in the various parishes	8
2018-02-21	**Monymusk Sugar Estate, Clarendon** *The sugar factory is not operating and therefore the fields are not taken care of.* *We drove around by ourselves and did not speak to anyone, so we only have our own impressions.*	9
2018-02-22	**Agricultural Research and Innovation Facility, University of the West Indies, Mona Campus, St. Elisabeth** Dr. Ian Thompson (Project Manager) - Development of various kinds of flour based on technical and economic opportunities	10

3.1.3. Obtaining Results

While looking back at an interesting and inspiring field trip, the aim was to formulate design constraints for the Jamaican sugar sector from the information obtained during the fieldwork. The fieldwork analysis was not restricted to the sugar sector alone, due to the fact that the information gathered during the open discussions and observations about other agricultural crops than sugarcane was found useful and representative to understand the context of the sugar sector [meeting 1, 5, 6, 7 & 10, Table 3.1]. It is assumed that the analysis of the agricultural sector results in representative context-specific design constraints for the sugar industry. To be able to make sense of the information received during the fieldwork and translate the information into the context-specific design constraints the Technological Innovation System (TIS) framework is used, which is explained in the following section.

3.2. Technological Innovation System Framework

The Technological Innovation System (TIS) framework aims to describe the development of a technology in interaction with the system in which the technology is embedded [63–66]. The framework is based on the fact that understanding technical change implies creating insight in and understanding the dynamics between the incumbent technology and the incumbent system in relation to the emerging technology and the emerging system [67–69]. The TIS framework is particularly suitable in this research, as the focus of this thesis is at the interface between the development of a technical process and the feasibility of this process in the context. With the TIS framework, a better understanding can be gained about the dynamics between technologies and the Jamaican sugar industry. In addition, the TIS framework is mentioned in the research agenda for sustainable transitions as an approach that is appropriate to address the multi-dimensional and multi-actor characteristics of technical transitions [70].

To gain understanding in the dynamics between technology and its context, both the structure of the innovation system and the functioning of the technology in that system should be defined [63, 71]. Understanding the structure of a system implies knowing the various actors, institutions, and their networks involved in developing, adopting and using new technologies [13, 71, 72]. To map the functioning of a technology in a system, a set of system functions is used in the TIS framework, see Table 3.2. The system functions used in this thesis are knowledge development and diffusion, entrepreneurial experimentation, influence on the direction of search, market formation, resource mobilization, and legitimation [13, 63, 73–75]. The system functions are a measure of the chance that a technology will be successful in its context. For example, if in a system there is no space nor guts for entrepreneurial experimentation, changes observed in technical processes will be exceptional. In the same way, if a technology is not accepted and supported by the society (legitimation) it will be hard to embed the technology in the social system, despite for example the willingness of entrepreneurs and the available knowledge and financial resources.

Table 3.2: List of TIS system functions as used in this thesis [13, 63, 73–75].

Function	**...is the process of**
Knowledge development and diffusion	...learning by searching, learning by doing and learning by interacting. ...the breadth and depth of the current knowledge base, how that changes over time and how that is diffused and combined in the system.
Entrepreneurial experimentation	...turning the potential of new knowledge, networks and markets into concrete actions to generate and take advantage of new business opportunities. ...taking risky experiments which are necessary to cope with the uncertainties of innovation.
Influence on the direction of search	...incentives and pressures which push and pull actors into a new technological field, as well as set the agenda within the field. ...perceived opportunities for business related to the emerging technologies.
Market formation	...identifying and articulating demand and supply. ...creation of market places, as well as trade and support related to the new technology.
Resource mobilization	...obtaining financial resources needed for investments, human resources needed for skilled tasks and material resources needed for construction and operation of the new technology. ...partnering.
Legitimation	...gaining social acceptance and support. ...relevant actors considering the new technology as appropriate and desirable.

3.3. Fieldwork Analysis using the TIS Framework

Section 3.2 explains that the TIS framework requires that both the structure of the system and the functioning of the technology in the system should be known to be able to obtain a full picture of the dynamics of a technology in its innovation system. Therefore, section 3.3.1 describes the structure of the Jamaican sugar sector by explaining the various actors and actions in the sugar sector with a supply chain and section 3.3.2 explains the functioning of technologies in the Jamaican agricultural industry by giving the design constraints for the sugar industry.

3.3.1. Structure of the System

Figure 3.1 presents the structure of the Jamaican sugar sector in a supply chain. A supply chain describes the transformation of natural resources into finished products and includes the various actors, institutions, activities and resources involved [76]. In Figure 3.1, the supply chain is shown as a linear process. It could be questioned if a linear process is reflecting the system of the sugar sector properly. For example, the factories are dependent on the supply of sugarcane, but the farmers are also dependent on the uptake rate of the factories as the sugarcane has to be processed within 3 days to avoid deterioration as described in section 2.5. This latter scenario where the harvest of sugarcane is dependent on the sugarcane processing is not displayed in the supply chain in Figure 3.1. Another example of a circular activity not shown in the supply chain is the recycling of the leafy parts and nutrients of the sugarcane as fertilizers on the land. The non-linear aspects that are not depicted clearly in the supply chain will still be considered in this thesis.

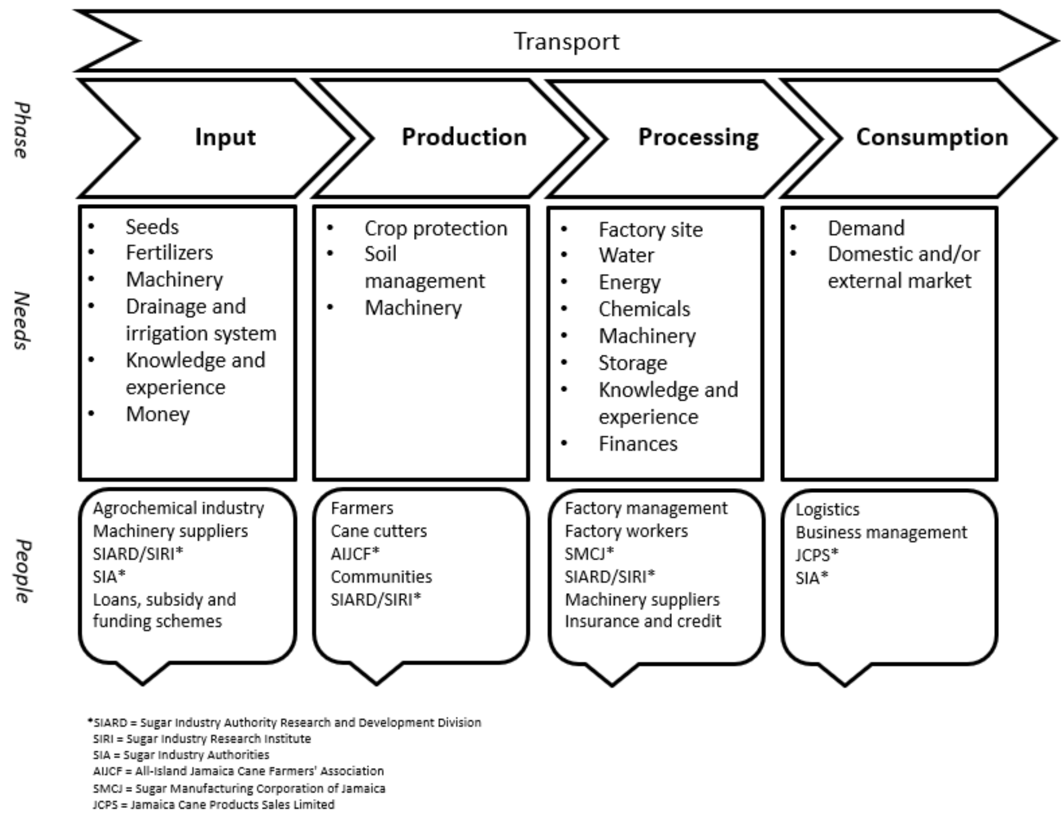

Figure 3.1: Supply chain of the sugar sector in Jamaica.

In the supply chain there are several phases that are connected by the transport between them. The phases are defined as the **input** for farming, the sugarcane **production** and harvesting, the **processing** of sugarcane in the sugar factory and the final **consumption** of the products. Each phase has several needs that must be satisfied to accomplish the phase. The input for farming and the sugarcane production and harvesting require all the resources to be able to plant the crop, maintain the crop and the land, and harvest the crop. This includes seeds, fertilizers, machinery, drainage and irrigation systems, knowledge and experience, and financial resources. To be able to process the sugarcane a factory site, utilities, chemicals, machinery, knowledge and experience, and financial resources should be available at the processing phase. The most important needs in the consumption phase are the existence of demand and the market. It is of essence for the well-functioning of the supply chain that all needs are satisfied. If, for example, during the sugarcane production and harvesting the crops and soil are not taken care of, a disappointing crop yield and sugar content can be expected despite a well-functioning input phase. In the same way, it is expected that an inefficient converting process in the sugar factory will result in significant economic losses, despite the supply of high quality sugarcane.

In every phase of the supply chain several actors, institutions and organizations are involved who can influence and/or are responsible for completion of the phase, see Figure 3.1. Some of the actors are already briefly mention in section 2.5. In and between the phases of the supply chain, the actors involved should have decent communication to be able to adjust to one and other and make the supply chain function well. The processing of sugarcane within the required 3 days is one example where communication between farmers and factory management is the key to success. Another example is that it is very important that the machinery and fertilizers are appropriately designed to be able to be used in maintaining the soil and sugarcane used in Jamaica. For this, the machinery suppliers and agrochemical industry of the input phase should be in close contact with the farmers, cane cutters and farmers' associations. Also, it is essential that research at and training given by the Sugar Industry Authority Research and Development Division (SIARD)/Sugar Industry Research Institute (SIRI) are aligned with what is actually done in the fields. This requires sufficient contact between SIARD/SIRI and the people working on the land. It should be noted that in all phases of the supply chain the Government of Jamaica is present, by the Sugar Industry Authority (SIA) who are regulating and monitoring the sugar industry and by extension officers of SIARD/SIRI who are aiming to improve the farming and industrial best practices.

3.3.2. Functioning of Technologies in the System

All meetings and visits described in Table 3.1 are included in the TIS framework, with the exception of the visit to the coffee estate. The other open discussions and observations during the fieldwork that did not directly relate to the Jamaican sugar industry are taken into account as they were found useful and representative to understand the context of the sugar industry [meeting 1, 5, 6, 7 & 10, Table 3.1]. All the field notes from the open discussions and observations taken by L. Asveld, Z. Robaey and myself during the fieldwork were analysed and summarized. The findings and insights from those field note summaries that were relevant to understand the context of the Jamaican agricultural industry are given in Appendix B. In Appendix B, the findings and insights are given as phrases of the conversations (the ones between quotation marks) and lessons learned. When a certain outcome followed from several open discussions and/or visits it was defined as a lesson learned. The lessons learned and phrases of the conversations given in Appendix B are structured according to the TIS system functions, which are described in Table 3.2. If a lesson learned or phrase of a conversation pertains to more than one system function it is indicated at both. For example, the lack of interest in the agricultural sector by young people, which leaves old farmers who are low in education and conservative in style behind, relates to both the system functions entrepreneurial experimentation and legitimation, see Appendix B.

The analysis on how technologies function in the Jamaican agricultural sector is based on the lessons learned and phrases of conversations obtained from the field notes given in Appendix B. The aim was to translate the field notes into design constraints. A constraint is a limitation or restriction imposed on an actor or activity. Therefore, the combination of the defined design constraints with previous described supply chain displays the boundaries within which the conceptual process design for the sugar industry can be developed.

The design constraints related to a certain TIS system function are extracted from the phrases of conversations and lessons learned obtained from the field notes also related to that specific TIS system function. The design constraints structured according to the TIS system functions are given in Table 3.3. The numbers behind the design constraints in Table 3.3 are randomly assigned and will be used in this thesis to refer to the design constraints. It should be noted that a constraint is not necessarily negative. For example, the growing awareness regarding the influences of climate change (13) demands strict measures that must be taken to mitigate change, but will also contribute to a more sustainable society.

For all the TIS system functions, constraints are observed that keep the Jamaican sugar industry away from functioning competitively and that show that the sugar industry is inefficient, see Table 3.3. To gain a better understanding on how the design constraints were formulated and how they influence the functioning of technologies in the sugar sector, the system functions with the associated constraints and field notes are elaborated in detail.

Table 3.3: Design constraints for the Jamaican sugar industry.

TIS Function	Design Constraints
Knowledge development and diffusion	• There is little interest among young people and entrepreneurs for farming and the agricultural sector, leaving old farmers low in education and conservative in style behind (1). • There is a big gap between scientific research and the actual farming and industrial practices (2). • There is insufficient communication between the various actors of the sugar industry (3). • Learning from words is not as effective as learning from experience (4). • The current way of working of farmers is not globally competitive (5).
Entrepreneurial experimentation	• There is little interest among young people and entrepreneurs for farming and the agricultural sector, leaving old farmers low in education and conservative in style behind (6). • Difficulty in adopting new technologies and maintaining existing ones (7). • There is a fear of change (8). • For farmers that are willing to experiment, a business case and working examples should be shown (9). • Setting up cooperations and collaborations to be able to share the uncertainties of innovation takes a lot of time and effort (10).
Influence on the direction of search	• There is a big gap between scientific research and the actual farming and industrial practices (11). • There is a lack of legislation to get new products in production and on the market (12). • There is a need to keep the deteriorating sugar industry alive (13). • There is a need for the creation of sustainable jobs (14). • Dependence on the government (15). • There is growing awareness regarding the influences of climate change (16).
Market formation	• Import gives security of quantity and quality and is easily organised compared to export or domestic production (17). • There is uncertainty about the effect of the Brexit on trading with the United Kingdom and the European Union (18). • There is a need to keep the deteriorating sugar industry alive (19). • Small farms face more difficulties compared to medium and large sized farms (20).
Resource mobilization	• Farmers do not have the financial resources to replant the field, so a lot of land is out of sugar (21). • Dependence on funding from community based organisations, government, grants and EU (22). • As the total capacity of the sugar factories is low, the total cost are higher compared to larger factories, due to economy of scale (23). • There is a lack of network utilisation (24). • Outdated equipment and aging farmers (25). • The roads are in a very bad condition (26). • There is a lack of access to technology (27).
Legitimation	• Lack of trust with bamboo-to-energy (28). • There is little interest among young people and entrepreneurs for farming and the agricultural sector, leaving old farmers low in education and conservative in style behind (29). • There is a lack of acceptance to get new products in production and on the market (30). • Distrust in the government and the country (31).

Knowledge development and diffusion

As described in Table 3.2 knowledge development is the process of learning by searching, learning by doing and learning by interacting. Besides that, knowledge diffusion is described as the process of how the current knowledge changes over time and how this knowledge is combined in the system. From the field notes, several insights are extracted that relate to the system function "knowledge development and diffusion", see Appendix B. The constraints for the "knowledge development and diffusion" function indicate that knowledge enhancement and transfer of knowledge from what is clear in theory to actual farming and industrial practices is requiring a lot of effort.

For example, we observed that there is tremendous effort in virology studies and in defining best farming practices to prevent crop diseases. However, we also observed that education is not related to farming, that there were hardly any applicants for the 'promising' Agricultural Entrepreneurship master at the University of the West Indies, that there is a gap between scientific data and the impact of this data, and that there is poor communication between cane cutters, farmers and the sugar factories. If there is no interest and diffusion of knowledge in the agricultural sector, changes and adjustments will highly unlikely occur despite the effort done in knowledge development. From those observations, constraints (1), (2) and (3) were defined which are describing the lack of interest, the knowledge gap and the insufficient knowledge transfer in the agricultural sector, see Table 3.3. To be able to deal with those constraints it is of essence that knowledge development, for example in new technologies, suits the context and that the knowledge about how to work with the new technology is transferred to the person that is actually going to work with the technology. In addition, we heard from several people that the opportunities in "smart" farming could spark the interest of young people in the agricultural sector.

Constraints (4) and (5) given in Table 3.3 are based on the field notes related to the system function "knowledge development and diffusion" about learning experiences and current practices, see Appendix B. We learned that only a relatively low yield of sugarcane per hectare can be achieved during harvesting and that the major cost in cassava flour production were coming from the purchase of raw materials. Regarding the implementation of improvements, we learned that it is not just a matter of writing the knowledge down in a report and give it to the person in charge. We observed that transfer of knowledge is more efficiently done through imitating working examples from for example neighbours, trough learning from experience, and by showing the opportunities to earn. For this, we observed that knowledge development and diffusion was increased when teaching was at the level of the community and if the community was used to transfer the knowledge. In addition, it was mentioned during an open discussion that the working combination is to give both technical training and education on how to be an entrepreneur.

Entrepreneurial experimentation

As described in Table 3.2 entrepreneurial experimentation is the process of turning the potential of new knowledge, networks and markets into concrete actions to generate and take advantage of new business opportunities. Alongside of that entrepreneurial experimentation is the process of taking risky experiments which are necessary to cope with the uncertainties of innovation. From the field notes, several insights are extracted that relates to the system function "entrepreneurial experimentation", see Appendix B. The constraints for the "entrepreneurial experimentation" function suggest that applying innovations and changes in the sugar industry will not be a straightforward and automatic process.

For example, we learned that there is a potential in diversification for the agricultural sector, there are (young) farmers that are willing to experiment, there is a preference to implement renewable energy technologies, and there are new entrants willing to restart the sugar factory at Monymusk. However, we also observed that there is a fear of change, a laziness to get up with new technologies and maintain the existing ones, a mismatch between business ideas and reality which is shown with the failed attempts to make jerk seasoning and jam, and that some sugar factories are already closed or about to close resulting in uncertainty about for example where to deliver the sugarcane. For the "knowledge development and diffusion" function it was already explained that there is a lack of interest in the agricultural sector by young people and entrepreneurs and that to the interested farmers a business case and working examples should be shown. Those insights and observations have resulted in the formulation of constraints (6), (7), (8) and (9), where constraint (6) is a repetition of constraint (1) and where constraints (7), (8) and (9) contain the difficulties of getting along with (new) technologies, the fear of change and the need to teach entrepreneurship, see Table 3.3. We observed that a possible solution to enlarge the entrepreneurial experimentation is to gradually implement innovations. For example, introduce mechanization into farming practices first only with those farmers that are interested. Probably, the neighbours will follow when good results are achieved due to the tendency to imitate, which is described by constraint (4), see Table 3.3. Also, it is of essence that new business cases, technologies and ideas match the context. For example, new technologies and machines should be appropriately designed for the farming and industrial practices, otherwise optimal conditions and results are extremely difficult to be met. This point was also emphasized in the discussion about the supply chain, see section 3.3.1.

Constraint (10) given in Table 3.3 is extracted from the quote "There is something in between the carrot and the stick model, called cooperation and collaboration, however this takes time and effort" and the question if the carrot model is a sustainable approach, see Appendix B. We observed that projects supported by the communities had more impact compared to projects organized from outside the communities that were using the carrot model of rewarding or the stick model of forcing. However, setting up projects in the communities and getting full support from the communities does take a lot of time and effort.

Influence on the direction of search

As described in Table 3.2 the influence on the direction of search is the process of incentives and pressures which push and pull actors into a new technological field, as well as set the agenda within the field. Also perceived opportunities for business cases related to emerging technologies can result in a search direction. From the field notes, several insights are extracted that relates to the system function "influence on the direction of search", see Appendix B.

In general, research can be an incentive to go into a certain direction and push actors into a certain field. However, as described for the "knowledge development and diffusion" function there is a gap between scientific research and the actual farming and industrial practices, see constraint (2) in Table 3.3. In addition, when we asked during an open discussion about the influence that research can have, it was mentioned that the farmers will not believe you on your research, but that you have to show them they need to change. Therefore, constraint (2) is also defined to be a constraint (11) for the "influence on the direction of search" function, see Table 3.3. Also, we learned that getting transgenic products in production was quite difficult. This means that although there are things going on in research, it is not guaranteed that this research is influencing the direction of the field. Constraint (12) emphasizes the difficulties in legislation encountered by translating research into practices, see Table 3.3.

The importance of the sugar industry in the current economy of Jamaica is following from various insights obtained during the fieldwork. We observed that thousands of jobs have to be saved for mostly uneducated people, that if the agriculture does not grow, the economy does not grow, and that there is no choice but to fight the deteriorating agricultural industry otherwise it will probably not survive. In addition, in the agricultural sector there is also an urgent need for mechanization and diversification, to reduce the cost of raw materials and to improve farming and industrial practices. Due to the important role of the agricultural industry in the economy of Jamaica and the urgent needs to keep the agricultural sector alive, there is an ambition from the industry itself and the government to strengthen the industry. The government does have a major influence in the direction of the field as they are present in all the phases of the supply chain and as with every election different choices can be made. Also, the government still has a large share in the agricultural sector despite the privatisation strategy, see section 2.5. Constraints (13), (14) and (15) are formulated based on the importance to keep the sugar industry alive, the needs that are related to this and the major role of the government, see Table 3.3.

The influence of the climate on the direction of search was mentioned directly or indirectly during every open discussion. An example of the influence of the climate on the island is the impact of hurricane Ivan in 2004. Ivan destroyed major parts of the land and left thousands of people homeless as a result of heavy rainfall, mud streams, and extreme wind. Because a large part of the agricultural land was destroyed, losses were faced in the agricultural industry and food became a scarcity. But also the less extreme dry and wet seasons are already affecting the harvesting yield and quality tremendously. Due to the growing awareness regarding the influence of climate change on daily life which is described by constraint (16), there is an interest to search for solutions how to adapt to and protect against climate change.

Market formation

As described in Table 3.2 market formation is the process of identifying and articulating demand and supply and market formation is the process of the creation of market places, trade opportunities and support for new technologies. From the field notes, several insights are extracted that relate to the system function "market formation", see Appendix B. The constraints for the "market formation" function point out that there is a high dependence on import from external markets. Therefore, it is required that the Jamaican sugar industry operates competitively global to be able to compete with the imported products.

For example, we learned that to export something is extremely difficult, bureaucratically speaking, while importing something is extremely simple. Also, the fact that domestic produced sugar costs more than the imported sugar and the question about how bio-ethanol can be produced globally competitive if sugar is not, show the difficulties for Jamaica to compete with the international market. In addition to that, import gives the security of a certain quality and quantity, which domestic production cannot achieve yet. Another example showing the major influence of the international market is the fall away of the preferential treatment and price agreements and the uncertainties arising on the trading with the United Kingdom and the European Union regarding to the Brexit. These findings are translated into constraints (17) and (18), which include the import-export difference and the uncertainties regarding the Brexit as an example for the dependence on external factors, see Table 3.3.

For the "influence on the direction of search" function it is observed that the importance of the sugar industry and the need to keep the deteriorating sugar industry alive have a major influence on the direction of the sugar sector. An important aspect of establishing a well-functioning industry is the existence of demand and a market as described in the discussion about the supply chain, see section 3.3.1. Therefore, constraint (13) is also defined to be a constraint (19) for the "market formation" function and emphasizes the need for demand and a market, see Table 3.3. A solution regarding market creation mentioned during an open discussion, was about seeing sugar as a by-product, while producing at the same time higher value-added products out of the sugarcane. This solution is in line with the principles of diversification and integration of the biorefinery concept explained in section 1.1.

We observed from several meetings that smaller farms obtain more difficulties compared to medium and large sized farms, due to the economy of scale and how the farms are managed. Because the consumption phase is dependent on all the previous phases in the supply chain and thus also on the sugarcane production phase, the difference obtained in the scale of farms is formulated in constraint (20), see Table 3.3. Constraint (20) should be taken into account by exploring the export opportunities and the opportunities to replace the import by domestic production. Because, if the farms are not able to produce at a certain quality, quantity and price then it will be hard for the sugar factories to deliver a product securing the quality and quantity. This interaction is also addressed as essential for the well-functioning of the sector in the supply chain description, see section 3.3.1.

Resource mobilization

As described in Table 3.2 resource mobilization is the process of obtaining financial resources needed for investments, human resources needed for skilled tasks and material resources needed for construction and operation of new technologies. In addition, the main requirement related to resource mobilization is the ability to build networks and having partners. From the field notes, several insights are extracted that relate to the system function "resource mobilization", see Appendix B. The constraints for the "resource mobilization" function indicate that both financial, human and material resources are currently not sufficiently available to implement new technologies or adjust existent technologies in the Jamaican sugar industry.

Regarding the financial resources, we observed that some farmers do not have money to replant the fields, that the responsibility for transport makes farmers economically weaker, that high land fees cannot be payed as not everyone can afford it to borrow money from the bank and that production of refined sugar is not feasible regarding the low capacity of the factories. In addition, it was more than once mentioned during the open discussions that money is urgently needed to replant the fields and to be able to provide equipment, knowledge and experience. We learned that a large part of the money is coming from funding from community based organizations, the government, grants and the European Union. We also observed that the money is not always going where it was intended, which is not very surprising in a country where corruption is present. The need for money to replant the fields, the dependence on external parties for funding and the capacity holding back innovations are included in constraints (21), (22) and (23), see Table 3.3. However, it could be questioned if just providing money is the right solution. A field note describes that the structure of providing for example seeds, chemicals and machines and pay them for keeping an eye seems more suitable compared to just giving money. In this case, the farmers are employed and can be controlled, while they still have their own land and only a part of the responsibility. During another open discussion it was mentioned that good extension means giving everything for free and emphasis has to be put on responsibility for the soil, the crop and the equipment. Although this sounds obvious, the solution can be probably found in a right balance between giving financial resources and strictness of what can be done with this money.

The "knowledge development and diffusion" function already indicates the lack of human resources. Some examples substantiating this are the fact that the sugar sector is dealing with aging and low educated farmers, that the current way of working is not globally competitive, that there is a gap between research and actual practices and that there is no decent communication between the different actors in the supply chain which is hindering the transfer of knowledge. From those insights and observations constraints (24) and (25) are formulated containing the lack of communication between the actors and the aging population of farmers, see Table 3.3.

Regarding the material resources, we observed that there is a lack of technology itself and a lack of knowledge on how to operate the technology, that the roads are in very bad condition and maintenance on the roads is not solving this, that there is a need for mechanization to make farming more efficient and that current equipment is aged. Constraint (25) includes besides the aging population of farmers also the outdated equipment as this was often mentioned together during the open discussions. Constraints (26) and (27) include the state of the roads and the lack of access to technology, see Table 3.3.

Legitimation

As described in Table 3.2 legitimation is the process of gaining social acceptance and support. Besides this, there should be relevant actors who consider the new technology as appropriate and desirable to actually make something happen. From the field notes, several insights are extracted that relate to the system function "legitimation", see Appendix B. From the constraints for the "legitimation" function the lack of support and trust for new technologies are standing out.

For example, we learned that a project about energy generation from bamboo encounters major hurdles to ground. This is among other things due to the fear of change, the conservative style of aged farmers, the lack of interest in the agricultural sector and the tremendous effort required to build the infrastructure and get the support from the community. Those aspects are mentioned in relation to the "knowledge development and diffusion" function and the "entrepreneurial experimentation" function as well. The example of the struggling bamboo-to-energy project is translated into constraint (28), which is an example for the lack of trust in new projects in general, see Table 3.3. Also, constraint (29) about the lack of interest in the agricultural sector is repeated for the "legitimation" function as this lack of interest has a major influence on the acceptance and the support of new technologies, see Table 3.3.

During the meetings, we observed a certain level of irritation about certain topics among the various persons we met. More than once it was mentioned that the government has a lot of influence on the sugar sector and that they are making plans, however this is not always seen in practice. From a research perspective it was mentioned that speaking to the farmers is not the problem, but them taking the advice is as the farmers do not trust the words of someone not from the field. The farmers and communities mentioned that they felt subordinated by the others in the supply chain as they are not listened to and they are not supported with what they need to keep going on. During an open discussion the current state of the sugar industry was called the era of depression accompanied by the low moral standard. For the sugar factories this era of depression is led by the fall away of the preferential treatment which makes it hard to sell their sugar and leaves them no time to invest in improvements and innovation.

Also, we learned that to convince someone, you have to approach him or her in the right way. In an open discussion it was mentioned that it is of importance to know the background of the person you are talking to and to show respect, otherwise you will not have a real open discussion. This has to do with the history of slavery and the associated difference made between black and white people. An example, where leadership and communication are properly executed is Worthy Park Sugar Estate. This estate is managed by the Clarke family since 1918, who are daily present in the factories and the field. It is believed that there presence and leadership has a major contribution to the well-function of the estate.

Another important aspect from the field notes related to the "legitimation" function is that we learned that if somethings goes wrong, now one will talk about it. This is because everyone is related to each other and in a culture of corruption and crime it is not recommended to be a whistle-blower. Constraint (30) emphasizes the difficulties encountered to get new products into production and on the market, see Table 3.3. A major reason for this is that the current system is not well-functioning and not properly organized, which makes implementing changes almost impossible. The distrust in the government and the country is included in constraint (31), see Table 3.3. Despite the irritations and hurdles, we also observed a spirit and passion among several actors in the Jamaican agricultural industry to keep fighting for the agricultural industry and the country in general.

4

Design Choices

The first section of this chapter contains a description of the design take-off. In the subsequent sections, the design take-off is step by step developed with five design choices into the context-specific conceptual process design for the Jamaican sugar industry. The design choices are extracted from the design constraints formulated from the field notes that were analysed with the TIS framework as described in chapter 3. Besides the design constraints, the principles of integration and diversification of the biorefinery concept are considered in the development of the process design.

4.1. Design Take-off

The complexity of a biorefinery increases tremendously when various types of raw materials and different technologies are integrated in one plant [12]. This can result in biorefineries of enormous size and with high-tech complex processes. In section 2.5 it was mentioned that the current sugar industry of Jamaica is low-tech and does not operate with high yields and efficiencies. Therefore, it seems quite out of context to propose such a large and complex high-tech biorefinery for the Jamaican sugar industry. This expectation is supported by several design constraints. For example, constraint (7) describing the difficulties in adopting and maintaining technologies, constraint (8) describing the fear of change and constraints (28) and (30) describing the lack of trust in and acceptance of the production of new products, see Table 3.3.

In this thesis, the design of the biorefinery for the Jamaican sugar industry is built up step by step taking the most simplest current situation as design take-off. With this approach the limits of a biorefinery in the Jamaican sugar industry can be found, but will not be exceeded as the feasibility of the process design in the context is reflected at every step. Figure 4.1 shows a schematic overview of the most simplest sugarcane process, which is taken as the design take-off. First, the sugarcane is chopped and washed, where after the sugarcane juice is squeezed out of the sugarcane leaving fibrous bagasse behind. Successively, the sugarcane juice is clarified to remove the non-sugar plant materials, concentrated to obtain a syrup, crystallized to form sugar crystals, and centrifuged to separate the raw sugar crystals from the mother liquor called molasse [77]. Molasse is used in the production of alcohol and in Jamaica especially in the production of rum. Sugarcane stalks and other leafy parts of the sugarcane are reused on the land as fertilizers and nutrients. The sugarcane stalks and molasses will not be encountered in detail in the design, but are included in stream Y, see Figure 4.1.

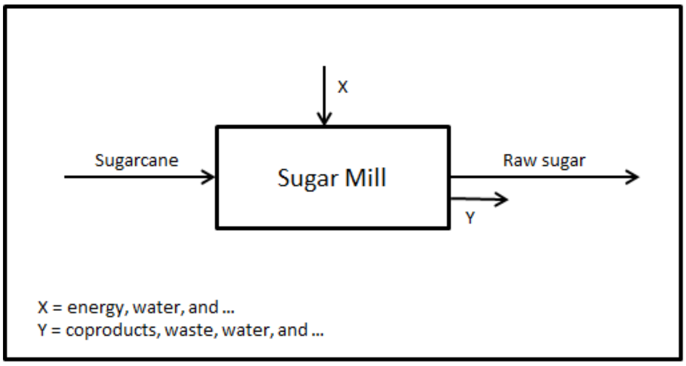

Figure 4.1: Schematic overview of the most simplest sugarcane process.

4.2. First Design Choice - Sugarcane as Feedstock

The first design choice is to stay with sugarcane as the only feedstock. With this, the decision is made not to change to another biomass crop, for example grass or bamboo, and even not to use multiple biomass crops including sugarcane. This decision is amongst others based on constraint (28), which describes the lack of trust in a bamboo-to-energy project, see Table 3.3. Although bamboo is growing everywhere in Jamaica, the fact that bamboo is not an agricultural crop resulted in a lack of trust holding back the projects progress.

Also, other constraints support the choice to stay with sugarcane and to not integrate other biomass crops at this moment. For example, constraint (7) describes the difficulties encountered in adopting new technologies and maintaining the existing ones, see Table 3.3. This is probably a result of constraint (27) that emphasizes the lack of access to technology and constraints (2), (3), (4) and (9) that describe the insufficient knowledge transfer, see Table 3.3. Other examples of constraints indicating that the transition from sugarcane to other biomass feedstocks will be challenging, are constraint (1/6/29) describing the lack of interest by young people and entrepreneurs in the agricultural sector leaving old farmers low in education and conservative in style behind, constraint (8) indicating the fear of change, and constraint (2/11) describing the gap between scientific research and actual farming and industrial practices, see Table 3.3.

Moreover, constraint (13/19) describes the urgent need to keep the deteriorating sugar industry alive as many people are directly dependent on it, see Table 3.3. It can be argued that those people will also have jobs if other crops than sugarcane are grown and processed. However, this will require more effort and time compared to reviving the sugar industry as this is already an established sector. Due to the foregoing reasons and mentioned design constraints it is proposed to stick to sugarcane as the trust and experience in sugarcane outweighs the for Jamaica-new-biomass crops. In addition, as multiple biomass feedstocks will increase the complexity of the design significantly, it is not proposed to combine sugarcane with other feedstocks, despite the fact that other biomass crops can be more promising in terms of for example energy yield and ease of harvesting [12].

If the sugar industry is revived by improving farming and industrial practices, by adapting new technologies and by a well-functioning of the supply chain, it is expected that the market position of the sugar industry is strengthened, the capacity enlarged, jobs created and a basis is created for innovation. The improvements and adaptations made to the sugar industry can be imitated when other biomass crops are used in the future as described by constraint (4), see Table 3.3. In this way, this first design choice contributes to a solid base laid down with the established sugar industry, where future incremental design of processing other biomass crops can build upon.

4.3. Second Design Choice - Plantation White Sugar and Anhydrous Bio-ethanol

The second design choice is based on the principle of diversification, which is mentioned in section 1.1. Diversification includes the simultaneous processing of multiple biomass feedstocks and/or production of several value-added products. Due to simultaneous processing and production, the economic and social risks are shared and therefore limited compared to the single processes [78]. The first design choice explains that only sugarcane is chosen as the biomass feedstock to stay with what suits the context of the sugar sector and to avoid a certain degree of complexity in the biorefinery. However, there are significant opportunities in producing various value-added products out of sugarcane. Examples of this mentioned in the first section of this chapter, are the use of sugarcane stalks as fertilizers on the sugarcane land and the use of molasses in the rum production.

In Jamaica, all the sugar factories produce raw sugar as their main product. Raw sugar has a lower value compared to refined sugar, see Table 5.1. The production of refined sugar in the Jamaican sugar sector is assumed not to be feasible due to the too low capacity of the existing factories, see constraint (23) in Table 3.3. The extra refinery steps needed to produce refined sugar are too capital intensive for the existent relatively small sugar factories due to the economy of scale. However, there is a way in between the lower-valued raw sugar and higher-valued technical and financial challenging refined sugar, that is plantation white sugar. Plantation white sugar has a higher value than raw sugar and only requires an extra clarification step after the sugarcane juice extraction. The clarification is done through carbonatation or sulphitation by adding carbon dioxide gas or sulphur dioxide gas to the sugarcane juice, respectively [79]. Figure 4.2 shows the schematic overview of the process design including the production of plantation white sugar out of the sugarcane juice.

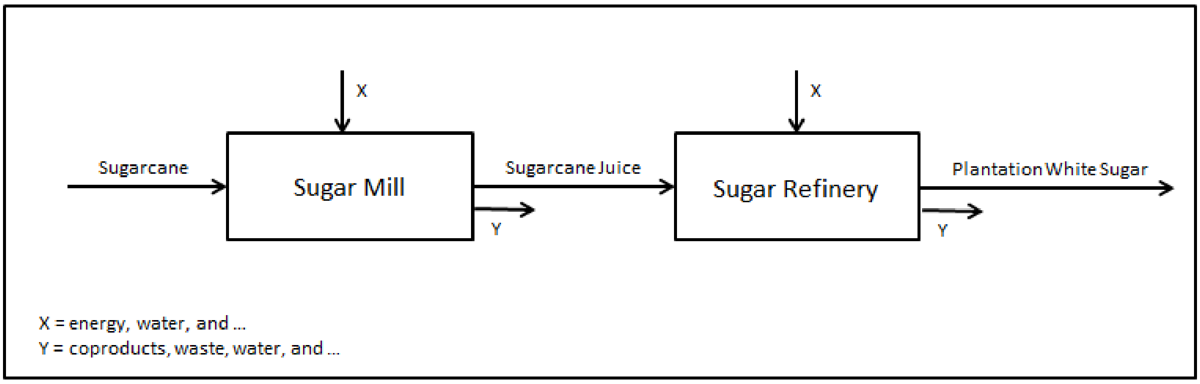

Figure 4.2: Schematic overview of the conceptual process design including plantation white sugar.

Plantation white sugar can (partly) replace the import of refined sugar in Jamaica, thereby enlarging the domestic demand for sugar and releasing an opportunity to increase the total sugar processing capacity. Less import and an increased domestic production are expected to support the self-sufficient sustainable bio-based economy in Jamaica. However, care should be taken as the use of plantation white sugar in comparison to refined sugar will increase the operating costs of manufacturers. Minister of Industry, Commerce, Agriculture and Fisheries, Karl Samuda has assured at a meeting of the Sugar Manufacturing Corporation of Jamaica (SMCJ) on January 31 of this year, that no decision will be taken using plantation white sugar as a substitute for refined sugar in the manufacturing process without agreement from members of the manufacturing sector [80].

Besides producing plantation white sugar, it is also chosen to produce anhydrous bio-ethanol out of sugarcane. How the sugarcane juice will be divided over the production of plantation white sugar and bio-ethanol will follow from further analysis on the proposed conceptual process design in the following chapters of this thesis. Blending of bio-ethanol with gasoline is mandated in Jamaica since March 2010 to increase the octane number and improve vehicle emissions [81]. This blended transportation fuel is called E10 and consists of 10% anhydrous bio-ethanol and 90% gasoline where the anhydrous bio-ethanol should have a purity of 99% to be able to use it in the fuel blends [82]. According to the Jamaica National Biofuels Policy 2010-2030, biofuels can increasingly satisfy the energy needs in an environmentally benign and cost-effective manner while reducing dependence on the import of fossil fuels and creating sustainable jobs [83].

Bio-ethanol is made by fermenting the sugarcane juice or a mixture of sugarcane juice and molasses. The production of bio-ethanol from sugarcane in Brazil is described in detail by De Souza Dias *et al.* [84] and Ensinas *et al.* [85, 86]. The main by-product from the bio-ethanol fermentation is vinasse. Vinasse is obtained after the distillation and removal of bio-ethanol, per liter bio-ethanol about 12 liters of vinasse are produced [87]. Vinasse is rich in minerals and is used as fertilizers on agricultural land [87]. Vinasse is not encountered in detail in this thesis, but is included in stream Y, see Figure 4.3. Nowadays, there is no anhydrous bio-ethanol production from sugarcane in Jamaica. However, there are several bio-ethanol dehydration plants based on azeotropic distillation to upgrade the imported bio-ethanol [88]. The Jamaican transportation sector consumed 6,186,00 barrels of gasoline in 2017, from this amount 4,470,000 barrels contained E10 fuel [89, 90]. As E10 consists of 10% bio-ethanol and a barrel is equal to about 159 liter, this results in about 71 million liters of bio-ethanol. All this bio-ethanol was thus not produced in Jamaica, but imported. If Jamaica wants to use its own produced bio-ethanol, it should be able to compete with the global prices of bio-ethanol and gasoline, which are around US$ 0.52 and US$ 0.54 per liter respectively [61, 91]. Figure 4.3 shows the schematic overview of the process design including both the production of plantation white sugar and anhydrous bio-ethanol from the sugarcane juice.

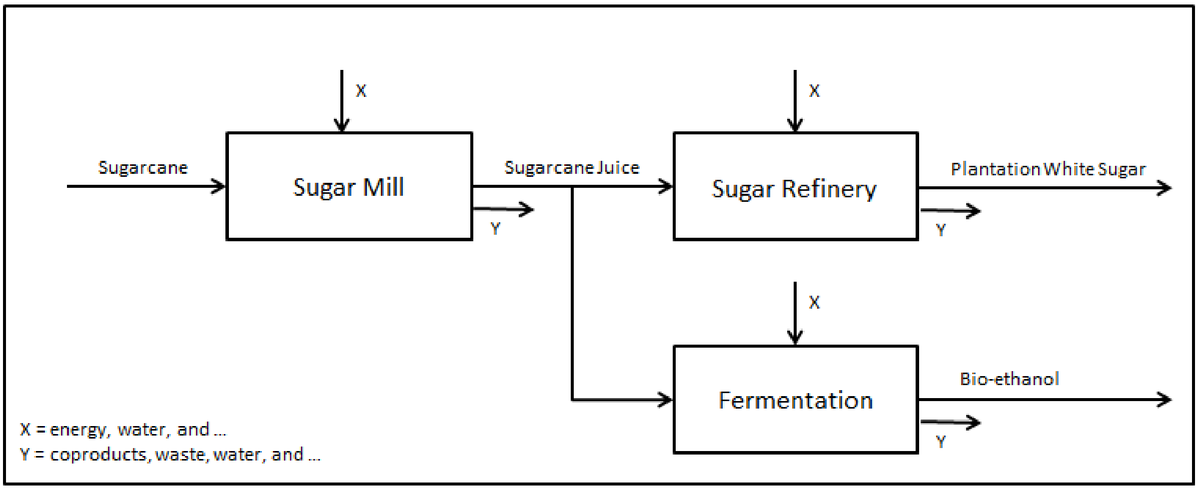

Figure 4.3: Schematic overview of the conceptual process design including plantation white sugar and bio-ethanol.

Due to the existent domestic market for bio-ethanol in the transport section, bio-ethanol has already overcome some design constraints. For example, constraints (12) and (30) describe that there is a lack of legislation and acceptance to get new products in production and on the market, see Table 3.3. Bio-ethanol already exists on the Jamaican market, which makes the lack of legislation and acceptance disappear. However, constraint (17) indicates that import gives the security of quantity and quality, see Table 3.3. As the import of bio-ethanol is already an established market, the 'home-made' bio-ethanol has to compete with the price and quality of imported bio-ethanol. Here, the government of Jamaica and other funding schemes have to play a role with the aim to support diversification to keep the sugar industry alive and establish the sustainable bio-based economy. This statement is supported by constraint (15) describing the dependence on the government, constraint (22) describing the financial dependence on funding from community-based organisations, the government, grants and EU, and constraint (13/19) indicating the need to keep the deteriorating sugar industry alive, see Table 3.3.

The production of bio-ethanol out of sugarcane juice requires the implementation and operation of new technical processes, among which the fermentors and the distillation towers. The implementation and operation of a new technology will not be straightforward in the Jamaican sugar sector, which is substantiated by several constraints emphasizing the difficulties that can be encountered by implementing a new technology. For example, constraints (3) and (4) related to the "knowledge development and diffusion" function suggest that the insufficient communication between the various actors in the sugar sector and the observation that learning from words is not as effective as learning from experience impede the development of the technology, see Table 3.3. Design constraints (7), (8) and (10) related to the "entrepreneurial experimentation" function are indicating the difficulties encountered in adopting new technologies, the fear of change and the time and effort required to set up cooperations where the uncertainties of innovations can be shared, see Table 3.3. In addition, design constraints (22), (24) and (27) related to the "resource mobilization function" indicate the dependence on funding, network utilisation and access to technology to be able to realise a new technology, see Table 3.3. However, the challenge of implementing and operating the new technical processes for the anhydrous bio-ethanol production are taken on as the feedstock, market and legitimacy for bio-ethanol in Jamaica are all out there already. An advantage is that the ethanol production out of sugarcane is a well-known process globally. Although, this is not a guarantee of success it gives the opportunity for actors in the Jamaican sugar industry to learn from the experience of others in the bio-ethanol production. In this case, the actors are not only being able to learn from words, but also from experience as advised by constraint (4), see Table 3.3.

By producing anhydrous bio-ethanol to satisfy the domestic market of E10 fuel, it is expected that the Jamaican sustainable bio-based economy is strengthened and that the dependence on import is reduced. Producing bio-ethanol for the external market is not considered as the demand for first generation biofuels is declining. Also, it will be very challenging for the Jamaican sugar sector to compete with the market price of bio-ethanol, which is set by the more established ethanol producing countries. In addition, the production of plantation white sugar and bio-ethanol are assumed to solve the problem of the overproduction of raw sugar in Jamaica. An overproduction of raw sugar is expected as a result of the declining raw sugar export and the process optimisations executed. The production of plantation white sugar and bio-ethanol can be the solution for this problem as due to diversification other markets can be reached.

4.4. Third Design Choice - Bagasse to Energy

The production of both plantation white sugar and bio-ethanol out of the sugarcane juice enhances the total amount of sugarcane as input to the sugar mill. From this amount of sugarcane, about 25% will leave the sugar mill as bagasse [46]. The third design choice is to convert the bagasse into electricity by a steam generator to satisfy the energy demand of the various processes. The generation of energy out of bagasse is both based on the principles of diversification and integration. Diversification by enlarging the range of utilized products and integration due to reuse of an output of the sugar mill process. The schematic overview of the conceptual process design including plantation white sugar, bio-ethanol and energy generation from bagasse is shown in Figure 4.4. In the schematic overview the energy stream is shown with a dashed line and is attached to stream X, which shows that it is intended to provide the sugar mill, the sugar refinery and the ethanol fermentation process with energy generated from bagasse.

By converting the residual bagasse into energy, the factory is able to (partly) operate on renewable energy. This will contribute to climate change mitigation globally and is in line with constraint (16) describing the growing awareness regarding the influences of climate change in Jamaica, see Table 3.3. In addition, energy generation out of bagasse is expected to support the establishment of the self-sufficient sustainable bio-based economy in Jamaica as a local renewable resource is used to generate energy instead of imported fossil fuel.

In the harvest season 2016/2017, about 450,000 tonnes of bagasse with a moisture content between 45-55% were obtained as by-product from the sugar mills, see Table 5.2. Based on the caloric value, this is equivalent to about 585,000 barrels of oil with a value of about US$ 41 million [92, 93]. Unfortunately, the boilers installed in the Jamaican sugar factories have low efficiencies of less than 10% [46]. They were designed to maximize the amount of bagasse used as excess bagasse was not desired and selling electricity to the grid was not an option [46, 94]. Nowadays selling to the grid is still not possible for all the factories and for the ones it is, only a fourth of the selling-price of electricity is offered [94]. Those aspects pose major barriers to develop the efficiency and capacity of the boilers. Several design constraints indicate the importance of sufficient resources, support and a direction of search to make a technology function well in the context. For example, constraints (12), (27) and (30) describe the lack of legislation, lack of technology and lack of acceptance to get new products, in this case energy generated from bagasse, in production and on the market, see Table 3.3.

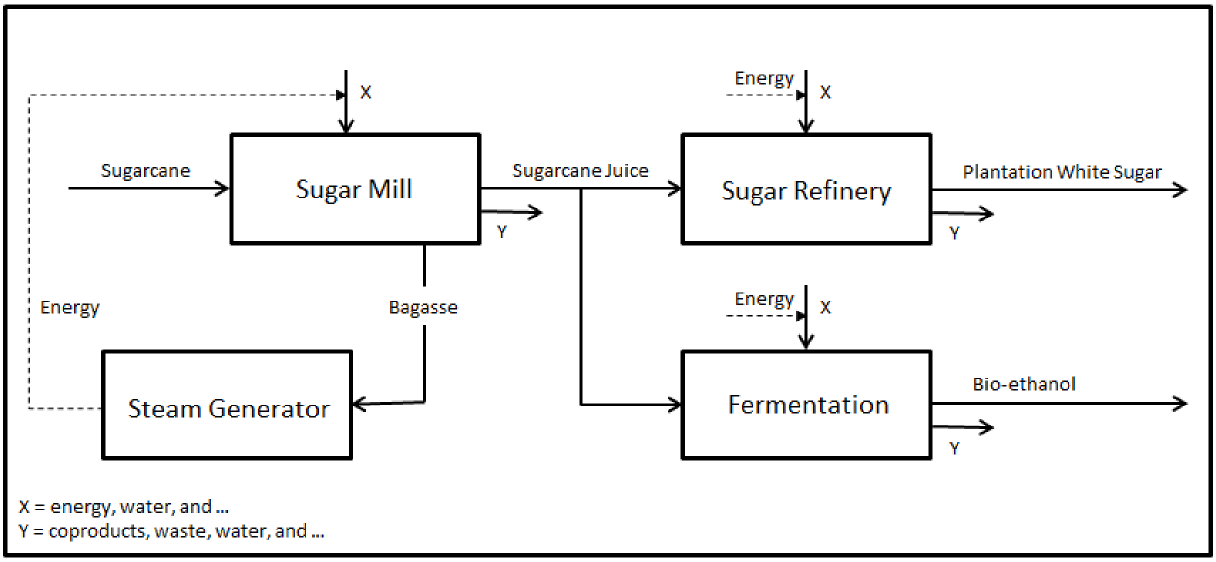

Figure 4.4: Schematic overview of the conceptual process design including plantation white sugar, bio-ethanol and energy generation from bagasse.

The energy generation from bagasse requires the installation and operation of high efficiency steam turbines and steam driven mills. The implementation and operation of new equipment is expected not to be straightforward in the Jamaican sugar sector, as already described in the case of bio-ethanol production, see section 4.3. Another important aspect in the energy generation from bagasse is the storage and transport of bagasse, because of the fact that bagasse is susceptible to spontaneous combustion and dust explosions [95, 96]. Despite the significant challenges expected in the implementation and operation of the high efficiency steam turbines and steam driven mills, and in the storage and transport of bagasse, the energy generation from bagasse is included in the proposed conceptual process design as in order to keep the sugar industry alive some effort needs to be made, see constraint (13/19) in Table 3.3.

An advantage with regard to the energy generation from bagasse is that the feedstock, market and technology are out there already. Bagasse is excessively available as feedstock because bagasse is a residual product from the sugar mills, that is now seen as by-product. The existence of a market for energy generated from bagasse is shown by a well-established energy market in Jamaica lead by the Jamaica Public Service Company Limited (JPS). In addition, the demand for energy during sugarcane processing is a non-erasable fact. Also, the technology to generate heat and energy out of bagasse through combustion in boilers is common knowledge and already used in Jamaica. However, the currently used boilers are outdated and not operating at the highest efficiencies possible. Due to the available feedstock, the existence of the market, the knowledge and experiences with the technology, and also the contribution to reduce the dependence on imported fossil fuel by using local renewable resources, it is expected that this third design choice will have a significant contribution to the viability and sustainability of the Jamaican sugar industry.

4.5. Fourth Design Choice - Bio-pellets

The fourth design choice is focusing on the external markets and the future opportunities to support the establishment of the self-sufficient sustainable bio-based economy in Jamaica. Renewable energy is becoming more and more important globally due to climate change mitigation, this is shown by countries setting themselves targets for energy from renewable resources. Not all countries are as fortunate as Jamaica to be surrounded by an excessive amount of bio-based resources. This suggests that the surplus of bio-based resources entail a great export opportunity for Jamaica. The IBIS project of the Delft University of Technology has several partners from industry, of which one is Bioforever. Bioforever is an European bio-based industry consortium demonstrating the feasibility of converting lignocellulosic feedstocks into chemical building blocks and value-added products [97]. If Jamaica is able to deliver this lignocellulosic feedstock at a desired quality, quantity and price, companies like Bioforever are standing in line to negotiate.

Bio-based resources can be converted into bio-pellets, which are considered promising for transportation as they have a high-density and are easy to handle [98]. Bio-pellets can be used for heat generation by burning or as a carbon source for chemicals [99]. Bio-pellets can be made out of various biomass feedstocks, including bagasse. A Dutch company called Viride SuStra B.V. is collaborating with the Delft University of Technology and they are specialized in the technology to produce bio-pellets from various lignocellulosic feedstocks. Their high-density "Green Pellets" are water resistant and can be enzymatically hydrolysed without previous steps, which makes them particularly suitable for transport and the use in biorefineries.

Figure 4.5 shows the schematic overview of the process design including the production of plantation white sugar, bio-ethanol and bio-pellets and the energy generation from bagasse. It is intended to also provide the pelleting process with energy generated from bagasse according to design choice 3 as described in section 4.4. The input of energy is displayed with the dashed line attached to stream X, see Figure 4.5. How the bagasse will be divided over energy generation and bio-pellet production will follow from further analysis on the proposed conceptual process design in the following chapters of this thesis. The production of bio-pellets out of bagasse requires several mechanical processing steps, including chipping, drying and pressing. In addition, bagasse can be pretreated by steam explosion before pelleting, which will increase the mechanical strength, hydrophobicity, calorific values and bio-chemical conversion of the produced bio-pellets [100, 101].

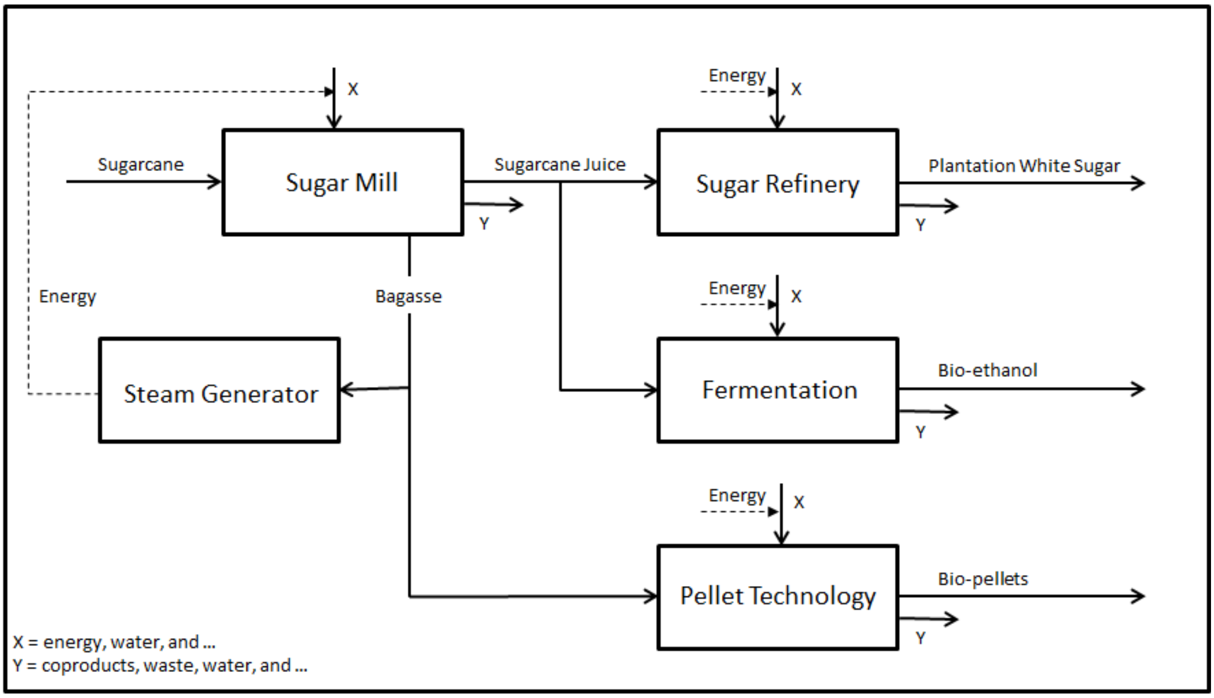

Figure 4.5: Schematic overview of the conceptual process design including plantation white sugar, bio-ethanol, energy generation from bagasse and bio-pellets.

To let the technology of producing bio-pellets function well in the sugar sector of Jamaica, the constraints especially related to the "entrepreneurial experimentation", "market formation" and "legitimation" functions should be carefully considered. It is assumed that if there is social acceptance, a market created and if there are entrepreneurs willing to invest in this pellet technology, the material resources and knowledge development will not pose major barriers. The technology to produce bio-pellets from bagasse is a well-known technology and can be done on a small and a large scale. However, the pellet characteristics can be significantly improved to obtain bio-pellets with increased mechanical strength, calorific value, enzymatical degradability, and of a higher value. The technology to produce bio-pellets needs to be experimented and some entrepreneurs should take the risk of being one of the firsts in this business in Jamaica. Constraints (7), (8), (9) and (10) from the "entrepreneurial experimentation" function indicate the importance of putting time and effort in the adoption of a new technology, in listening why people are afraid of the change and inform them of what is happening, in showing the business case and working examples, and in setting up cooperations to be able to share the uncertainties of the innovation, see Table 3.3.

The market for bio-pellets is increasing due to the renewable targets set in countries policies. However, the bio-pellet market is not in its most elaborated phase yet. An example of this is the scandal of using wood pellets from the United States to generate power in the United Kingdom, which was mentioned in section 1.1. Another difficulty encountered is that Jamaica has not participated in the bio-pellet market yet. Constraint (17) from the "market formation" function indicates the importance of considering the position of Jamaica in the global market and the possibilities to export products regarding for example legislation, see Table 3.3. Regarding the "legitimation" function, constraints (28), (29), (30) and (31) emphasize the need of trust, interest and acceptance from the actors involved, including the government, in the bio-pellet technology to enhance the change of succeeding, see Table 3.3.

Dealing with the aforementioned constraints related to the "entrepreneurial experimentation", "market formation" and "legitimation" functions is not expected to be an easy task. However, the production of bio-pellets from bagasse is expected to be a feasible option to revive the sugar sector and it gives the opportunity for a new export market. The production and export of bio-pellets can establish the global market position of Jamaica in the growing trade of renewable products. With this, not only the self-sufficient sustainable bio-based economy of Jamaica is supported but also the global sustainable bio-based economy, which is in line with constraint (16) describing the growing awareness regarding the influences of climate change, see Table 3.3. In addition, the implementation and operation of the pellet technology in the sugar industry will make it easier in the future to use other biomass crops as feedstock for bio-pellets, for example bamboo or grass. This is because of the possibility to imitate how the pellets are produced from bagasse, the confidence gained in bio-pellets enhancing the legitimation and the proven market feasibility of bio-pellets. In this way, the production of bio-pellets from bagasse can be seen as a diversification step that increases value, strengthens the position of the sugar industry both domestically and abroad, and creates opportunities for future businesses.

4.6. Fifth Design Choice - Enough is Enough

The fifth design choice is titled: Enough is Enough. This means that the design showed in Figure 4.5 is the proposed conceptual process design for the Jamaican sugar industry. In section 4.1 it was explained that a large and complex high-tech biorefinery is out of context for the Jamaican sugar industry. Therefore, the conceptual process design of a biorefinery that suits the context was built up step by step to find the limits of what is still expected feasible. The first four design choices propose the diversification of the Jamaican sugar industry by producing both plantation white sugar, anhydrous bio-ethanol and bio-pellets and the integration by generating energy out of bagasse. It is expected that with those diversification and integration steps the limits for the current sugar sector are reached as the proposed design comes along with significant challenges, which were substantiated with design constraints in the previous sections discussing the design choices.

Technical challenges include the installation of new equipment, the operation of the new technical processes and the optimization of current farming and industrial practices. The production of plantation white sugar requires a small adaptation to the current processes, while the production of anhydrous bio-ethanol and bio-pellets require completely new technical processes, see sections 4.3 & 4.5. The bagasse-to-energy process is not completely new in the Jamaican sugar sector, see section 4.4. However, significant enhancement of the process yields and reduction in the use of steam and power during the processes by using energy conservation techniques and energy efficient equipment is needed to satisfy both the energy and bio-pellets demand from bagasse. In addition, the farming and industrial practices should be improved to transform the current low-tech sugar sector into a well-functioning globally competitive sector.

As mentioned in section 1.1, the entire chain of utilizing biomass into value-added products is much more complex than the technical feasibility alone. So, besides the technical challenges it is of tremendous importance to take the social and economic challenges into account to confirm the feasibility of the technical process in its context. The section about the supply chain emphasizes that all actors and activities have to be aligned in order to make the sugar industry function well, see section 3.3.1. Therefore, constraints (4), (10) and (22) indicating the insufficient communication between the various actors, the time and effort required to set up cooperations and the lack of network utilisation really need to be taken serious, see Table 3.3. Also, the observations that the current way of farming is not globally competitive, that learning farming practices is best achieved through experiences and that business cases and working examples should be shown to farmers suggest that a lot of time and effort should be spent on the improvement of the production phase in the supply chain, see constraints (5), (3) and (9) in Table 3.3.

An important factor from an economic point of view is the fact that the strategy to privatize the sugar sector requires a high degree of transparency, clear rules, improvements in the investment environment, no games in the background, no shadow interests, and no conflicts of interest between the actors [61]. Those requirements are indispensable to make the sector attractive for investors.

The proposed conceptual process design for the Jamaican sugar industry only has a change to function well if both the technical challenges have been overcome, the phases and needs in the supply chain are satisfied, the transport along the supply chain is well-functioning, the communication between the various actors is sufficient, and if there is support from the government and the people of Jamaica. The proposed conceptual process design for the Jamaican sugar industry as shown in Figure 4.5 is considered to be complex and challenging enough for now. However, this does not mean that other options could not be considered in the future. Examples of completely new options with regard to the proposed design are on-site enzyme production for ethanol fermentation, bio-gas production from for example vinasses, CO_2 utilization, on-site waste water treatment and the production of chemical building blocks from bio-based resources. The use of other feedstocks in, for example, energy generation and/or bio-ethanol and bio-pellet production can be achieved by incrementally developing the processes of the proposed design.

5
Database

The previous chapter explained step by step the development of the context-specific conceptual process design for the Jamaican sugar industry. To further develop the proposed design, the details of the material balances and the costs involved to install and operate the processes are described in chapter 6 and chapter 7, respectively. The data provided in this chapter is used to define the process constants and process variables in the material balances and to assess the financial viability of the proposed design. The first two sections of this chapter contain data about the prices and quantities related to the Jamaican sugar industry. The third section contains literature data on the yields and quantities that could not be obtained from the Jamaican sugar industry, which is due to the fact that the proposed design includes processes which are not currently in operation in the Jamaican sugar industry and also because of insufficient data gathering and communication in the Jamaican sugar sector.

5.1. Jamaican Sugar Industry - Prices

Table 5.1 shows the market prices of sugarcane, of the utilities and of the products related to the Jamaican sugar sector in 2018. In addition, the market price for refined sugar and anhydrous bio-ethanol are given as those products are currently imported in Jamaica. The electricity (feed-in) price of 0.10 US$/kWh is the price at which locally-generated electricity is purchased, while the electricity price of 0.40 US$/kWh is the price at which electricity is sold to consumers. It is not surprising that this low price for locally-generated electricity holds back the implementation of more efficient energy generation processes and the production of surplus electricity.

Table 5.1: Market prices related to the Jamaican sugar sector in 2018.

		Unit	*Source*
Price of feedstock			
Sugarcane	7.4	US$/t	0.62*raw sugar price [49, 82]
Price of utilities			
Water	1.54	US$/$m^3$	[102]
Electricity	0.40	US$/kWh	[61, 94, 103]
Electricity (feed-in)	0.10	US$/kWh	[94]
Price of products			
Raw sugar	12	US$/t	Contract No 11 [50, 58]
Refined sugar	300	US$/t	Contract No 5 [50, 59, 60, 104–106]
Anhydrous bio-ethanol	0.52	US$/l	[61, 107, 108]

5.2. Jamaican Sugar Industry - Quantities

Table 5.2 shows the amount of sugarcane land and sugarcane used, the quantities in the raw sugar production and the consumption of raw sugar related to the Jamaican sugar sector for the harvest season 2016/2017. The harvest season 2016/2017 is chosen, because the data for the harvest season 2017/2018 was not available yet at the moment of writing. It is assumed that the data for the harvest season 2016/2017 is comparable and representative to the current harvest season as no significant changes in the sugar sector were observed between those seasons [meeting 2, 3, 4 & 8, Table 3.1]. Table 5.2 also contains the consumption of refined sugar and anhydrous bio-ethanol in 2016/2017, although those products are not produced in Jamaica. The consumption demand of raw sugar, refined sugar and bio-ethanol in Jamaica is assumed to be representative for the domestic demand in the coming years, while the export of raw sugar is expected to decrease tremendously [61].

Table 5.2: Quantities related to the Jamaican sugar sector for the harvest season 2016/2017.

		Unit	*Source*
Sugarcane land			
Total	56,700	ha	[49]
Planted	35,000	ha	[48]
Harvested	30,000	ha	[48]
Sugarcane			
Total	1,800,000	tc	[48]
Yield	60	tc/ha	*own calculation*
Sugar content	12-17	%	[53, 109–112]
Production			
Raw sugar	140,000	ts	[48]
Yield	0.08	ts/tc	*own calculation*
Bagasse	450,000	t	*own calculation*
Yield	0.25	tb/tc	[46]
Moisture content	45-55	%	[46, 49]
Consumption			
Raw sugar (domestic)	60,000	ts	[48]
Raw sugar (export)	80,000	ts	[48]
Refined sugar (import)	70,000	ts	[48, 61]
Anhydrous bio-ethanol (import)	71,000,000	l	[89, 90]

5.3. Literature Data - Quantities

This section includes literature data about the processing yields and the energy and water demand of the proposed processes in the conceptual design. The data about the yield of bio-ethanol from sugar and of bio-pellets from bagasse is extracted from literature as those products are not currently produced in Jamaica. The data about the energy yield from bagasse is extracted from literature as this data was not available from the Jamaican sugar factories. The data about the energy and water demand for the combined sugar and bio-ethanol production and the energy demand for the pelleting process is extracted from literature as the integrated sugar-ethanol process and the pelleting process are not currently operated in Jamaica.

5.3.1. Bio-ethanol Yield

The maximum theoretical yield of ethanol from sugar or dextrose is determined with the Gay-Lussac equation, which is as follows [107]:

$$C_6H_{12}O_6 \longrightarrow 2C_2H_5OH + 2CO_2 \tag{5.1}$$

With molar masses of respectively 180.16 g/mol, 46.07 g/mol and 44.01 g/mol, this equation results in the following mass balance (%):

$$100.00 \longrightarrow 51.14 + 48.86 \tag{5.2}$$

From this it follows that the maximum theoretical yield is 51.14 mass units of ethanol produced per 100.00 mass units of dextrose. Taking into account the formation of by-products as glycerol and various kinds of acids, the maximum practical yield from the Gay-Lussac equation is determined at 48.34 mass units of ethanol produced per 100.00 mass units of dextrose [107]. When the mass unit of 51.14 is set at 100%, the mass unit of 48.34 is 96.4%. Ethanol yields between 88-94% are considered good in practice and yields between 84-88% are not surprising for fermentors installed in the 1970s and 1980s [107, 113].

To be able to translate this ethanol-dextrose yield into an ethanol-sugarcane yield, the sugar content in the sugarcane should be known. In literature, the sugar content in sugarcane is defined with a maximum at 17% and a range between 12-17% [53, 109–112]. Table 5.3 shows the amount of bio-ethanol (96% and 100% pure) in liters per tonne of dextrose and per tonne of sugarcane based on the Gay-Lussac equation for a sugar content of minimal 12% and of maximal 17%. It is assumed that the density of ethanol is 0.789 kg/l at a temperature of 20°C [107]. From Table 5.3 it follows that the amount of bio-ethanol per tonne of sugarcane with a purity of 100% is at maximum 107 l/tc when the sugar content equals 17% and the Gay-Lussac yield equals 94%. A minimum bio-ethanol yield of 65 l/tc is observed when the sugar content equals 12% and the Gay-Lussac yield equals 84%, see Table 5.3. In literature, ethanol-sugarcane yields are reported around 74-88 l/tc [52, 82, 84, 109, 110]. Yields lower than 65 l/tc have not been found in literature and are assumed to be economically infeasible.

Table 5.3: Ethanol yields based on Gay-Lussac equation, assuming an ethanol density of 0.789 kg/l at a temperature of 20°C [107].

Yield based on Gay-Lussac equation	**Liter bio-ethanol/tonne dextrose**		**Liter bio-ethanol (100% pure)/tonne sugarcane**	
	100% pure	*95% pure*	*Sugar content 12%*	*Sugar content 17%*
84%	544	561	65	95
86%	557	575	67	98
88%	570	588	68	100
90%	583	601	70	102
92%	596	615	72	105
94%	609	628	73	107

5.3.2. Bio-pellet Yield

Bagasse is the fibrous material that is left after the sugarcane juice extraction. Each tonne of sugarcane yields about 250-300 kg of bagasse, depending on the fibre content of the sugarcane which normally ranges from 12 to 19% [46]. As described for design choice 4 , bio-pellets can be produced from bagasse and they can be used for heat generation by burning or as a carbon source for chemicals, see section 4.5. Pelleting has several advantages over raw biomass, as with pelleting the moisture content is reduced and the density is increased, which results in an increase in energy content of pellets compared to the raw biomass [98, 114, 115]. The density of pellets is about six times higher than the density of raw biomass, shown by a density increase from about 120 kg/m^3 to 720 kg/m^3 [98, 115–117].

Depending on the pelleting process, the bagasse is mechanically reduced to a certain particle size and dried to a certain moisture content [98, 114, 117]. For pelleting without any pretreatment of the biomass, the preferred particle size is about 3-10 mm and the moisture content is about 7-12% [98, 115, 117]. The moisture content is an important characteristic of the biomass in the pelleting process. A too low moisture content will result in incoherent pellets as there is not enough water to act as glue. But also a too high moisture content will result in incoherent pellets as the surplus of water is acting as a barrier between bonding molecules [118, 119]. The large amount of thermal energy needed in the drying process to reduce the moisture content from about 55% to 10% requires high operating costs [117]. After chipping and drying the bagasse is pelletized under a certain temperature and pressure. The pelleting conditions are dependent on the biomass and the desired pellet quality. Finally, the pellets are cooled and packed for storage and transport [114, 117].

The bio-pellet yield from bagasse is obtained by calculating how much the moisture content is reduced and by taking into account process losses, which are assumed to be 10%. For example, from 100 kg bagasse with 50% moisture, about 60 kg bio-pellets with 10% moisture can be produced. From this 60 kg, 10% will be lost during processing, resulting in 54 kg of bio-pellets from 100 kg of bagasse. This gives a yield of 0.54 tonne bio-pellets per tonne bagasse.

5.3.3. Energy Yield from Bagasse

Bagasse can also be used directly to generate heat and energy through combustion in boilers. In most sugarcane factories, the bagasse obtained after sugarcane juice extraction is burned in a co-generation system based on the Rankine cycle [84]. With the produced steam electric generators are driven, which provide the electromechanical energy demand of the mills extracting the sugarcane juice from the bagasse. In addition, the backpressure steam is used to satisfy the thermal requirements of the various operation units in the sugar production [120].

Table 5.4: Energy generation from bagasse taking into account the moisture content, system efficiency, lower calorific value (LCV) and higher calorific value (HCV). LCV = [18,260 - 207.63*moisture% - 182.6*ash% - 31.14*brix%] kJ/kg and HCV = [19,605 - 196.05*(moisture% + ash%) - 31.14*brix%] kJ/kg, assuming ash% and brix% equal 5% and 2%, respectively [79, 121].

			System efficiency (HCV)		
Moisture %	*kJ/kg (HCV)*	*kWh/ton (HCV)*	*kWh/ton (5%)*	*kWh/ton (10%)*	*kWh/ton (25%)*
45.0	9,743.0	2,706.4	135.3	270.6	676.6
47.0	9,351.0	2,597.5	129.9	259.8	649.4
49.0	8,959.0	2,488.6	124.4	248.9	622.2
50.0	8,763.0	2,434.2	121.7	243.4	608.5
51.0	8,567.0	2,379.7	119.0	238.0	594.9
53.0	8,175.0	2,270.8	113.5	227.1	567.7
55.0	7,783.0	2,161.9	108.1	216.2	540.5
			System efficiency (LCV)		
Moisture %	*kJ/kg (LCV)*	*kWh/ton (LCV)*	*kWh/ton (5%)*	*kWh/ton (10%)*	*kWh/ton (25%)*
45.0	7,928.0	2,202.2	110.1	220.2	550.6
47.0	7,512.0	2,086.7	104.3	208.7	521.7
49.0	7,096.0	1,971.1	98.6	197.1	492.8
50.0	6,888.0	1,913.3	95.7	191.3	478.3
51.0	6,680.0	1,855.6	92.8	185.6	463.9
53.0	6,264.0	1,740.0	87.0	174.0	435.0
55.0	5,848.0	1,624.4	81.2	162.4	406.1

The higher caloric value (HCV) and lower caloric value (LCV) of a tonne bagasse with a moisture content of 50% are respectively, 8,763 kJ/kg and 6,888 kJ/kg, see Table 5.4 [79]. This means that one tonne of bagasse is equivalent to about 1.3 barrels of oil with an energy content of 6,120 kJ/kg [92]. However, the higher the moisture content in bagasse, the lower the calorific value. A moisture content of 45% can be obtained from a sugar mill with good practices, while poor milling practices will result in bagasse with a moisture content larger than 52% [46, 121].

Another factor, besides the moisture content, that is highly influencing the amount of energy that can be generated from bagasse is the efficiency of the boiler. A low-pressure boiler (20-25 bar) in combination with an extraction-condensing and/or backpressure steam turbine coupled to an electrical generator results in system efficiencies less than 10%. While, with high-pressure/high-temperature boilers (45-66 bar) system efficiencies up to 25% can be achieved [85]. Bagasse with a moisture content of 50% and burnt in a boiler of 25% efficiency will result in about 600 kWh (HCV) of energy per tonne of bagasse, see Table 5.4. Theoretically, the available energy from bagasse combustion exceeds the energy demand in the production of sugar and ethanol from sugarcane [120, 122].

5.3.4. Water Demand for Production of Raw Sugar and Bio-ethanol

In the production of raw sugar and bio-ethanol water is particularly used for washing, dilution, cooling and as boiler feed water. A study comparing the bio-ethanol production from sugarcane in the USA and Brazil reports an effective water input of 21 l water/l anhydrous bio-ethanol for both countries [52]. In this study the anhydrous bio-ethanol yield is assumed to be about 1 l of bio-ethanol from 12-14 kg of sugarcane, which is equal to 77 l bio-ethanol/tonne sugarcane. Taking into account a yield of 77 l/tc, the water consumption results in about 1,615 l/tc. In addition, it was mentioned that in the bio-ethanol distillation and dehydration about 10 l water/l bio-ethanol had to be removed to obtain anhydrous bio-ethanol with a purity of 99.5% [52].

Another study regarding the sustainability of the bio-ethanol production from sugarcane in Brazil, also emphasizes the large amounts of water needed in the conversion of sugarcane to bio-ethanol [123]. It is noted that much more water is needed in the processes than just the consumption demand as there is also water recycled in the system. For example, for washing the sugarcane in a standard wet sugarcane washing process about 5 m^3 water/tc is used [123]. The study reports that the total water consumption decreased substantially from 5.6 m^3/tc in 1997 to 1.83 m^3/tc in 2004 [123]. The 1,830 l/tc given in this sustainability study is in the same range of the total water consumption of 1,615 l/tc reported in the aforementioned study [52, 123].

A study concerning water reuse and recycling in a sugarcane mill in Brazil producing both sugar and bio-ethanol from sugarcane with a 50/50 production ratio, reports a total water use of 15,071 l/tc [124]. This total water use includes amongst others water for cooling, cleaning and washing. The effective water demand by the sugar-ethanol process is reported to be 1,229 l/tc, which is only 8% of the total water use [124]. In this study it is also mentioned that sugarcane washing accounts for 20% of the total water use, so about 3,000 l/tc [124]. Another study also reports that 25% of the total water use is taken by the washing process [86].

In addition, in the study about water reuse and recycling it is emphasized that imbibition of water during the milling process accounts for the largest share of the effective water demand, about 300 l/tc from the 1,129 l/tc in total [124]. Other articles report an amount of imbibition water of 235 l/tc [125], 250 l/tc [120] and 360 l/tc [126]. A study analyzing the reduction in water-usage in sugar and bio-ethanol production from sugarcane with a 50/50 production ratio, reports a total water use of 13,188 l/tc and an effective water demand of 1,132 l/tc [127].

In Table 5.5 the above mentioned effective water demands in the production of sugar and bio-ethanol are summarized. A possible reason for the reduced water demand in the integrated production of sugar and bio-ethanol compared to a stand-alone bio-ethanol production is the use of the aqueous by-product, molasses, from the sugar production as input in the bio-ethanol fermentation.

Table 5.5: Effective water demand of sugarcane processing in Brazil.

	Liter water / tonne sugarcane	*Source*
Bio-ethanol production	1,615	[52]
	1,830	[123]
Sugar and bio-ethanol production	1,229	[124]
	1,132	[127]

5.3.5. Energy Demand for Production of Raw Sugar and Bio-ethanol

The energy demand in the processes to convert sugarcane into raw sugar and bio-ethanol is due by mechanical energy, electrical energy and thermal energy. In this thesis, it is assumed that the thermal energy demand is satisfied by the backpressure steam from the turbines providing the mechanical and electrical energy.

The study comparing the bio-ethanol production from sugarcane in the USA and Brazil reports a total energy input of 392 kWh/l of anhydrous bio-ethanol for both countries [52]. With a yield of 77 l anhydrous bio-ethanol/tc, this results in a total energy demand of about 30 kWh/tc. This value is in line with a study analyzing the process steam demand and electricity generation in sugar and bio-ethanol production from sugarcane in Brazil, which reports a total energy demand of 28 kWh/tc [85]. This 28 kWh/tc is compiled of the mechanical energy demand of sugarcane preparation and sugarcane juice extraction (16 kWh/tc) and the electrical energy demand of the other process units (12 kWh/tc) [85]. In two other studies the mechanical energy demand for sugarcane juice extraction using a mill is reported to be 20 kWh/tc [125] and 18 kWh/tc [120]. A study concerning the economic analysis of bio-ethanol and electricity production from sugarcane in South Africa reports also an overall energy demand of 28 kWh/tc for a factory using a mill for sugarcane juice extraction [126].

In another study an exergy analysis on the various process units in sugar and bio-ethanol production is performed to evaluate the irreversibility generation in each unit separately [86]. The electrical power demand of the sugar process is reported to be 5,250 kW and the electrical power demand of bio-ethanol process including sugarcane preparation, sugarcane juice extraction and treatment is reported to be 3,000 kW. Taking into account the model basis of operating for 4,000 h with a total amount of 2,000,000 tonnes of sugarcane crushed during the harvest season, this results in an electrical energy demand of 10.5 kWh/tc for sugar production and of 6.0 kWh/tc for bio-ethanol production from sugarcane [86].

In Table 5.6 the above mentioned energy demands in the production of raw sugar and bio-ethanol are summarized.

Table 5.6: Energy demand of sugarcane processing into raw sugar and bio-ethanol.

	kWh / tonne sugarcane	*Source*
Total energy demand	30	[52]
	28	[85, 126]
Mechanical energy demand of	16	[85]
sugarcane preparation and	20	[125]
sugarcane juice extraction	18	[120]
Electrical energy demand		
Sugar and bio-ethanol production	12	[85]
Sugar production	10.5	[86]
Bio-ethanol production	6	[86]

5.3.6. Energy Demand for Production of Bio-pellets

The energy demand in the process to make bio-pellets out of biomass is particularly due by sizing, drying and pelleting the biomass and by cooling the bio-pellets. A study performing a systems analysis on the entire densification process of wood into wood pellets, reports a total energy demand of 3,383 MJ/tonne wood pellets if the bio-pellet plant uses wood pellets as fuel and of 3,777 MJ/tonne wood pellets if the plant is fueled by sawdust [128]. The higher energy demand for using sawdust as fuel for the plant is due to the low combustion efficiency of sawdust requiring a higher thermal energy input [128].

Another study investigated the use of steam explosion pretreatment to produce durable wood pellets and reports a total direct energy input of 4,830 MJ/tonne wood pellets. In this total direct energy input the collection of the biomass, transportation and other miscellaneous units were taken into account [119]. The total direct energy input of sizing, drying, pelleting and cooling alone is reported to be 4,400 MJ/tonne wood pellets of which drying accounted for 2,900 MJ/tonne wood pellets [119]. The energy demand of 4,400 MJ/tonne wood pellets [119] is higher compared to the aforementioned energy demands of 3,383 and 3,777 MJ/tonne wood pellets [128], this can be the reason of several factors ranging from the quality of the wood to the efficiency of the equipment.

The production of sugarcane bagasse pellets required a total energy input of 5320 MJ/tonne bagasse pellets as reported in another study [117]. The total energy demand of 5,320 MJ/tonne bagasse pellets is divided into thermal and electrical energy, where thermal energy accounts for 4,810 MJ/tonne bagasse pellets and electrical energy for 510 MJ/tonne bagasse pellets. [117]. The higher energy demand for the production of bagasse pellets compared to wood pellets is most probably due to the higher initial moisture content of bagasse, that is about 55% for bagasse and about 45% for wood [117, 119].

The influence of the initial moisture content of the biomass on the energy demand is also shown in a study concerning the switchgrass production in a European setting [129]. In this study, an electricity demand of 94 MJ/tonne switchgrass pellets is given [129], which is significantly lower than the electrical energy demand of 510 MJ/tonne bagasse pellets mentioned earlier [117]. This energy demand difference is due to the fact that switchgrass has an initial moisture content of about 20% and bagasse of about 55%, which results in much less energy required in drying of switchgrass to obtain the required 7-12% moisture [129]. Another study about the thermodynamics of energy production from biomass, reports a total electricity requirement of 547 MJ/tonne wood pellets, where the wood pellets had an initial moisture content of 55% [130]. This electricity demand of 547 MJ/tonne wood pellets of which the wood pellets contain an initial moisture content of 55% is comparable with the electricity demand of 510 MJ/tonne bagasse pellets mentioned earlier [117, 130].

In Table 5.7 the above mentioned energy demands for the production of bio-pellets from various types of biomass are summarized.

Table 5.7: Energy demand for the production of bio-pellets. The initial moisture content of the biomass is given between brackets.

	MJ / tonne bio-pellets	*Source*
Total energy demand		
wood pellets fueled by wood (45%)	3,383	[128]
wood pellets fueled by sawdust (45%)	3,777	[128]
wood pellets (45%)	4,400	[119]
bagasse pellets (55%)	5,320	[117]
Electrical energy demand		
bagasse pellets (55%)	510	[117]
switchgrass pellets (20%)	94	[129]
wood pellets (55%)	547	[130]
Thermal energy demand		
bagasse pellets (55%)	4,810	[117]

The energy consumption of the pelleting part specifically is described in several studies. In the study performing a systems analysis on the entire densification process of wood into wood pellets, the specific energy consumption for densification is given for various types of biomass; sawdust requires 36.8 kWh/t, bark+wood requires 30-45 kWh/t and switchgrass requires 74.5 kWh/t [128]. Another study analyzing the pelleting characteristics of selected biomass with and without steam explosion pretreatment, reports a specific energy consumption for pelleting of 70-90 kWh/tonne biomass (barley, canola, oat and wheat), where the biomass had an initial moisture content of 13-16% [115]. The specific energy consumption for bagasse pelleting is reported in another study to be between 112-150 kWh/tonne bio-pellets depending on the moisture content and equipment efficiency [131]. Assuming a pellet yield of 0.50 tonne bio-pellets/tonne bagasse, this results in a specific energy consumption of 56-75 kWh/tonne bagasse, which is in the same range as the other studies mentioned.

From the study investigating the use of steam explosion pretreatment to produce durable wood pellets a much higher energy input of 185 kWh/tonne wood is obtained [119]. A total direct energy input of 1,110 MJ/tonne wood pellets is reported, where the initial moisture content of the biomass is 45% [119]. With a yield of 0.6 tonne bio-pellets/tonne wood, the total direct energy input results in about 667 MJ/tonne wood, which is equal to 185 kWh/tonne wood. In addition, it is mentioned that the press mill has a power capacity of 220 kW [119]. Also, in another study about the development of agri-pellet production a power requirement for the pellet mill of 300 kW is reported to be able to densify biomass residues from wheat, barley and oats [114]. The reason that these two studies report much higher energy demands for pelleting can be due to the size of the equipment. The studies obtaining the high energy demands were performed for pellet plants with a production capacity of 45,000 tonne bio-pellets/year [119] and 44,000 tonne bio-pellets/year [114]. With the increase in the size of the pellet mill the friction values are expected to increase resulting in a higher specific energy requirement [115, 128].

In Table 5.8 the above mentioned energy and power demands of the pelleting process for various types of biomass are summarized.

Table 5.8: Energy and power demand for the pelleting process.

	kWh / tonne biomass	*Source*
Specific energy consumption		
sawdust	36.8	[128]
bark+wood	30-45	[128]
switchgrass	74.5	[128]
wheat straw	90	[115]
barley straw	70	[115]
canola straw	90	[115]
oat straw	80	[115]
bagasse	56-75	[131]
wood	185	[119]
	kW / tonne biomass	*Source*
Power of pellet mill		
wood	220	[119]
wheat, barley, oats	300	[114]

6

Material Balances

To further engineer a process design a sequence of flow diagrams is generally used. In the first section of this chapter, an example is given that shows that the material balances in the flow diagram of the proposed design are highly dependent on the process variables. Therefore, in the second and third sections the process constants and variables of the conceptual process design are explained in more detail. A summary of the process constants and variables as considered in this thesis is provided in section 6.4. In section 6.5, the influence of the process variables on the material balances is investigated. The chapter concludes with an overview of potential yields of the process variables, which are suggested to be most feasible in the context taking into account various initial choices.

6.1. Flow Diagram

Three main types of flow diagrams are described by Seider *et al.*, beginning with the simplest block flow diagram (BFD), proceeding to the process flow diagram (PFD), and concluding with the piping and instrumentation diagram (P&ID) [132]. The BFD represents the main processing sections in terms of functional blocks and indicates the overall material balances. A PFD displays all of the major processing units in the process, provides stream information and includes the main control loops that enable the process to be regulated under normal operating conditions. The P&ID is the design document transmitted by the process design engineers to the engineers responsible for plant construction, start-up and operation.

The BFD of the proposed context-specific conceptual process design is equal to the design given in Figure 4.5, but includes the overall material balances. To be able to construct the BFD and give a financial overview of the proposed conceptual process design, information is needed about the process constants and process variables in the material balances. In Figure 6.1 the process constants are indicated with a letter and the process variables are indicated with a number. The process constants are a) the bagasse yield (tb/tc), b) the bio-pellet yield (tp/tb) and c) the energy demand for processing (kWh/tc or kWh/tb). The process variables are 1) the sugarcane yield (tc/ha), 2) the plantation white sugar yield (ts/tc), 3) the anhydrous bio-ethanol yield (l/tc) and 4) the energy yield from bagasse (kWh/tb).

Setting up the material balances for the proposed process design is not straightforward. In a demand based scenario the production of plantation white sugar should be around 130,000 tonnes and the production of anhydrous bio-ethanol should be around 71,000,000 liters, see Table 5.2. For simplicity, plantation white sugar is abbreviated with PWS and anhydrous bio-ethanol is also called bio-ethanol. It is assumed that the demand of PWS is equal to the amount of raw sugar domestically consumed plus the amount of refined sugar imported. The export of sugar is not taken into account as this is expected to decline tremendously in the future [61]. If the 130,000 tonnes of PWS and the 71 million liters of bio-ethanol are produced with the current processing yields as given in Table 5.2, about 45,300 hectares of sugarcane land are required. This amount of hectares is within the 56,700 hectares of sugarcane land available, but does exceed the 30,000 hectares of sugarcane land that is currently harvested, see Table 5.2. This example shows that one or more process variables should be optimized to be able to align the material balances with the context.

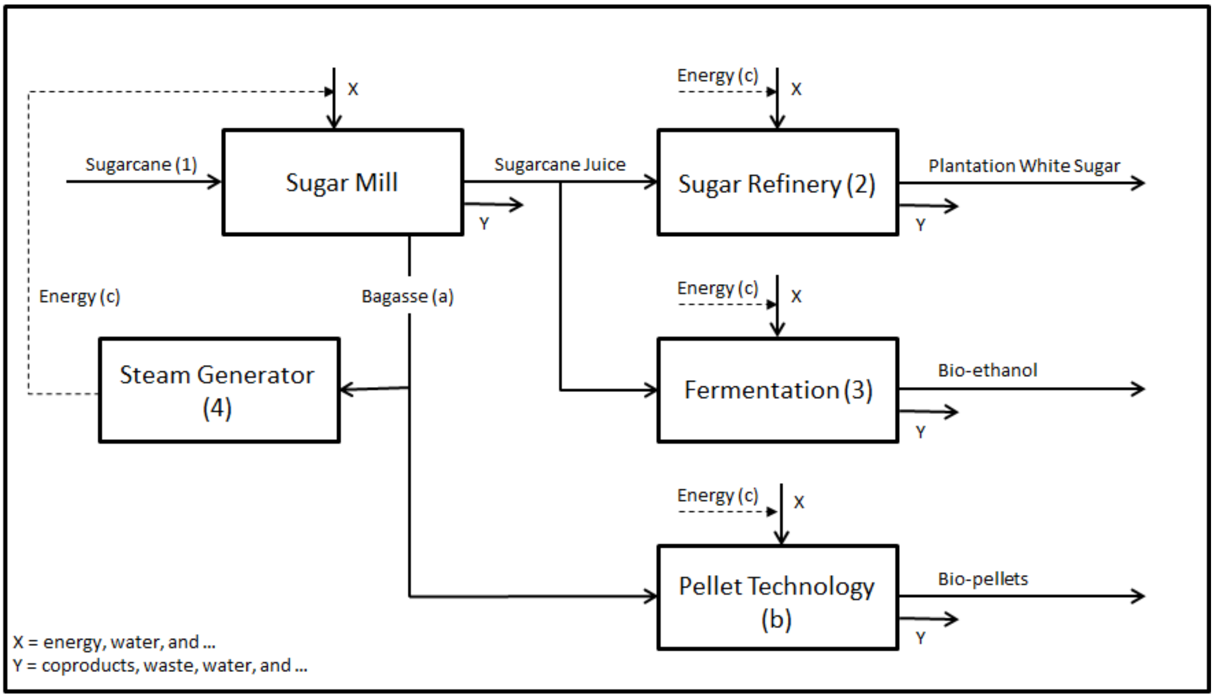

Figure 6.1: Schematic overview of the proposed conceptual process design including process constants (letters) and process variables (numbers).

6.2. Process Constants

The amount of bagasse obtained during the sugarcane processing, the amount of bio-pellets produced from bagasse and the energy needed to operate the production processes are set to be fixed in the proposed process design. In this section, the process constants with their values as considered in this thesis are explained. The letters in the headings of the following subsections refer to the context-specific conceptual process design in Figure 6.1.

6.2.1. Bagasse Yield (a)

As already stated in section 5.3.2, bagasse is a by-product from the sugar production and is obtained as a fibrous material after the sugarcane juice extraction. Each tonne of sugarcane yields about 250-300 kg of bagasse, depending on the fibre content of the sugarcane which normally ranges between 12 and 19% [46, 117]. In this thesis, the lowest bagasse yield is taken as design basis to avoid an overestimation of the process. Therefore, a bagasse yield of 0.25 tb/tc is used in the calculations for the material balances and in the following parts of this thesis.

6.2.2. Bio-pellet Yield (b)

In the Jamaican sugar industry 2016/2017, 450,000 tonnes of bagasse with a moisture content of about 45-55% were obtained as a by-product from the sugar mills, see Table 5.2. In this thesis, a moisture content of 55% is taken as the design basis as this high moisture content requires the most energy during processing. The required moisture content for pelleting is about 10%, which results in the fact that the moisture content of bagasse has to be reduced from 55% to 10% during a drying process, see section 5.3.2. From 100 tonne bagasse with a moisture content of 55%, about 55 tonne pellets with a moisture content of 10% can be produced. As described in section 5.3.2, it is assumed that the losses over the whole pelleting process are 10%, which results in an overall yield of about 49.5 tonne bio-pellets per 100 tonne bagasse. Therefore, a bio-pellet yield of 0.5 tp/tb is used in the calculations for the material balances and in the following parts of this thesis.

6.2.3. Energy Demand for Processing (c)

The total energy demand for processing is coming from the production of sugarcane juice, PWS, bio-ethanol and bio-pellets, see Figure 6.1. Based on the various literature studies concerning the energy demand for the production of sugar and bio-ethanol a total energy demand of 30 kWh/tc is suggested in this thesis for the production of plantation white sugar and anhydrous bio-ethanol out of sugarcane, see section 5.3.5. This total energy demand includes about 16-20 kWh/tc for the mechanical energy demand of sugarcane preparation and sugarcane juice extraction and about 10-12 kWh/tc for the electrical energy demand, see Table 5.6.

Section 5.3.6 entails the energy demand for the production of bio-pellets from various types of biomass feedstock. The total energy demand of 5,320 MJ per tonne of bagasse pellets is considered to be reasonable in comparison with the lower energy demands of other biomass feedstocks due to the fact that bagasse has a higher moisture content which requires more energy for drying. Taking into account the pellet yield of 0.5 tp/tb as explained in section 6.2.2 and by converting MJ to kWh, the total energy demand to produce bagasse pellets suggested in this thesis results in 740 kWh/tb. From this total energy demand about 10% is due by the specific energy consumption of the pelleting process, see Table 5.8.

6.3. Process Variables

The variables of the process design are the sugarcane yield, the plantation white sugar yield, the anhydrous bio-ethanol yield and the energy yield from bagasse. The process variables are divided into farming process variables and industrial process variables. The sugarcane yield is defined as a farming process variable, while the others are industrial process variables. In this section, the variables with the ranges of their values as considered in this thesis are explained. The numbers in the headings of the following subsections refer to the context-specific conceptual process design in Figure 6.1.

6.3.1. Sugarcane Yield (1)

In Table 5.2 it can be found that the sugarcane yield of the harvest season 2016/2017 in Jamaica was about 60 tc/ha. However, in section 2.5 it is mentioned that other countries can achieve 75-90 tc/ha. In this thesis a sugarcane yield range from 55-80 tc/ha is considered. Yields higher than 80 tc/ha are expected to be unrealistic for the Jamaican farming industry as they will require enormous changes and improvements in the farming best practices. The lower boundary of 55 tc/ha is taken into account as yields lower than 60 tc/ha can occur for example in years with extreme rain or drought.

6.3.2. Plantation White Sugar Yield (2)

The production process of plantation white sugar from sugarcane is not significantly different from the production process of raw sugar from sugarcane and therefore the yields are considered as equal in this thesis, see section 4.3. The raw sugar yield of the harvest season 2016/2017 in Jamaica was about 0.08 ts/tc (see Table 5.2), while in literature sugar yields of 0.10-0.12 ts/tc are reported as noted in section 2.5. In the calculations for the material balances and to analyse the influence of the PWS yield on the total amount of sugarcane and sugarcane land needed, a PWS yield range from 0.07-0.12 ts/tc is considered. The minimum of 0.07 ts/tc indicates the below business-as-usual situation and the maximum of 0.12 ts/tc shows the situation when the sugar production is at a globally competitive level.

6.3.3. Anhydrous Bio-ethanol Yield (3)

To analyse the influence of the bio-ethanol yield on the material balances, a bio-ethanol yield range from 65-90 l/tc is considered. In Table 5.3 it is shown that for the lowest sugar content of 12%, a low Gay-Lussac yield of 84% and a high purity of 100%, the bio-ethanol yield is about 65 l/tc. This minimum scenario is taken as lower boundary of the bio-ethanol yield range as the Jamaican sugar industry is low-tech and low yields will not be that surprising as the production of anhydrous bio-ethanol is new in Jamaica. The higher boundary of 90 l/tc can be achieved if the sugar content in the sugarcane is approaching the 17% and if the installed equipment can achieve high yields and is operated appropriately.

6.3.4. Energy Yield from Bagasse (4)

To define the range of the energy yield from bagasse the moisture content and boiler efficiency are important factors. Unfortunately, it was not possible to obtain a more narrow range of the moisture content of bagasse than 45-55% from Jamaican sugar factories, see Table 5.2. Section 5.3.3 explains that poor milling performances will result in moisture contents higher than 50% and that this high moisture content will decrease the calorific value of the bagasse, which will result in a significant reduction of the energy yield. The lower boundary of the energy yield from bagasse is based on the high moisture content of 55% and a system efficiency of only 5%, which could be a possible scenario in the low-tech and not very efficient sugar industry of Jamaica. For this moisture content of 55% and a system efficiency of 5%, the LCV equals 81.2 kWh/tb and the HCV equals 108.1 kWh/tb, see Table 5.4. However, if Jamaica is installing high-pressure/high-temperature boilers with system efficiencies up to 25% and if they achieve moisture contents in the range of 45%, an energy yield of 550.6 kWh/tb (LCV) and 676.6 kWh/tb (HCV) can be obtained, see Table 5.4. Therefore, an energy yield range from 100-600 kWh/tb is considered in the calculations for the material balances and to analyse the influence of the energy yield from bagasse on the amount of bagasse required for energy generation and available for bio-pellet production.

6.4. Summary of Process Constants and Variables

In Table 6.1 the values of the process constants and the ranges of the values of the process variables as explained in sections 6.2 and 6.3 are summarized. The values will be used to analyze the influence of the process variables on the materials balances in the following section of this chapter.

Table 6.1: Summary of process constants and variables. The letters and numbers between brackets refer to the proposed context-specific conceptual process design in Figure 6.1.

		Unit
Process constants		
Bagasse yield (a)	0.25	tb/tc
Bio-pellet yield (b)	0.5	tp/tb
Energy demand for processing (c)		
• PWS and bio-ethanol	30	kWh/tc
• Bio-pellets	740	kWh/tb
Process variables		
Sugarcane yield (1)	55-80	tc/ha
Plantation white sugar yield (2)	0.07-0.12	ts/tc
Anhydrous bio-ethanol yield (3)	65-90	l/tc
Energy yield from bagasse (4)	100-600	kWh/tb

6.5. Material Balance Sensitivity

In this section the influence of the process variables on the materials balances is investigated. First, the effect of varying the sugarcane yield, the plantation white sugar yield and the anhydrous bio-ethanol yield within their defined ranges on the amount of plantation white sugar and anhydrous bio-ethanol that can be produced is studied. Second, the effect of varying the sugarcane yield and the energy yield from bagasse within their defined ranges on the amount of bagasse required for energy generation and the amount of bagasse available for pelleting is studied.

6.5.1. Production of Plantation White Sugar and Anhydrous Bio-ethanol

The production of sugarcane as function of the sugarcane yield is shown in Figure 6.2. The sugarcane yield is varied between 55-80 tc/ha, see Table 6.1. The harvested amount of sugarcane land is fixed at 30,000 ha according to the current harvested amount of sugarcane land in Jamaica, see Table 5.2. An increase in sugarcane land above the 30,000 ha is not considered in this thesis as it should be possible to produce the required amount of PWS and bio-ethanol from this amount of sugarcane land. In addition, the currently unused but potential sugarcane land could be used in the future to harvest other biomass feedstocks, for example energy crops. As sugarcane is a seven-years crop, the investment to plant sugarcane on the current unused land is expected to hold back the start of growing other biomass feedstocks.

The amount of sugarcane that can be produced from 30,000 ha of sugarcane land is between 1,650,000 tc for a sugarcane yield of 55 tc/ha and 2,400,000 tc for a sugarcane yield of 80 tc/ha, see Figure 6.2.

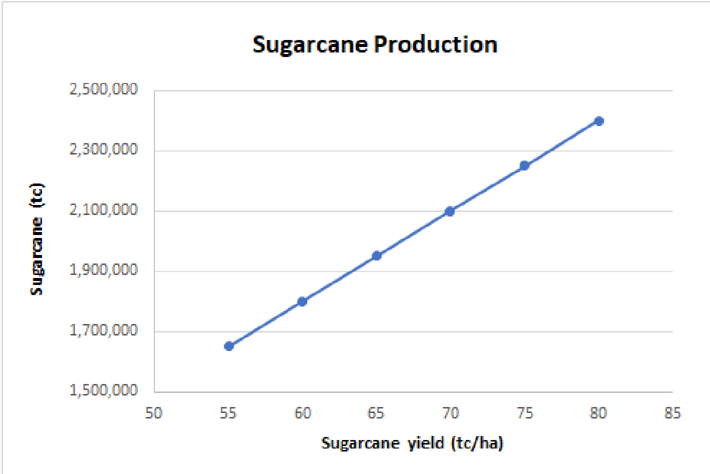

Figure 6.2: Sugarcane production as function of the sugarcane yield. The amount of sugarcane land is set equal to 30,000 ha.

In Figure 6.3, the demand of sugarcane as a function of the PWS yield and bio-ethanol yield is given. The demand of PWS and bio-ethanol are fixed at 130,000 ts and 71,000,000 l, respectively. This is in accordance with the consumption of raw sugar, refined sugar and anhydrous bio-ethanol in Jamaica, see Table 5.2. A minimum amount of about 1,870,000 tonnes of sugarcane is required to satisfy the demand of PWS and bio-ethanol, see Figure 6.3. To obtain this minimum amount of sugarcane, the PWS yield is equal to 0.12 ts/tc and the bio-ethanol yield is equal to 90 l/tc. Those values are the maximum values of the considered ranges, see Table 6.1.

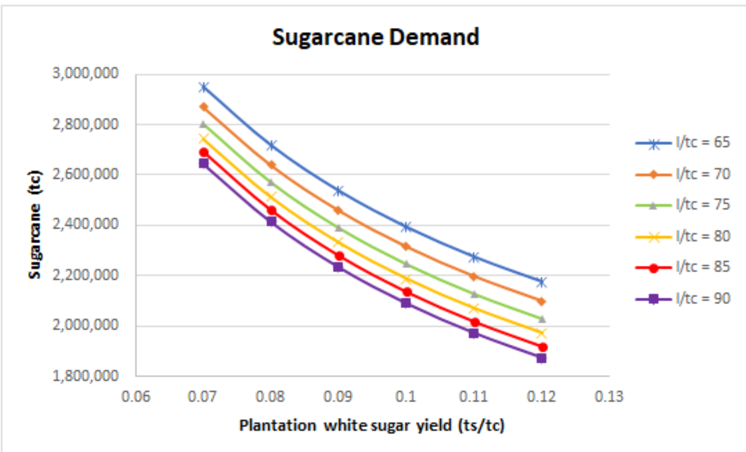

Figure 6.3: Sugarcane production as function of the plantation white sugar yield and anhydrous bio-ethanol yield. The amount of plantation white sugar is set equal to 130,000 ts and the amount of anhydrous bio-ethanol is set equal to 71,000,000 l.

A remarkable fact extracted from Figure 6.2 and Figure 6.3 is that when the PWS yield and the bio-ethanol yield are as optimized as suggested feasible in this thesis, the amount of sugarcane required to satisfy the demand is higher compared to the sugarcane that can be produced when the sugarcane yield equals 55-60 tc/ha. In other words, the demand of 130,000 tonnes of PWS and 71,000,000 l of bio-ethanol cannot be achieved if the sugarcane yield is 60 tc/ha or lower, if a PWS yield of max 0.12 ts/tc and a bio-ethanol yield of max 90 l/tc are assumed. Therefore, a sugarcane yield of 65 tc/ha or higher is recommended if there is a preference to domestically produce the 130,000 tonnes of PWS and 71,000,000 l of bio-ethanol.

A possible reason for a reduced domestic production of PWS and the allowance of the import of refined sugar is the increased operating costs of manufactures when using PWS instead of refined sugar as explained in section 4.3. Another reason is that the import of refined sugar and bio-ethanol are already established and that as described by constraint (17) import gives security of quantity and quality and import is easily organised compared to export and domestic production, see Table 3.3. This does not mean that all products should be imported as this will not support the self-sufficient sustainable bio-based economy in Jamaica. However, there is a possibility to partly produce PWS and bio-ethanol domestically and partly import those products if for example a sugarcane yield of 65 tc/ha cannot be achieved in the short-term.

To study the influence of the sugarcane yield, the PWS yield and the bio-ethanol yield on the amount of PWS and bio-ethanol that can be produced, the amount of bio-ethanol produced is calculated by the following equation:

$$\text{Ethanol (l)} = \text{ethanol yield (l/tc)} * (\text{sugarcane yield (tc/ha)} * \text{sugar land (ha)} - \frac{\text{PWS (ts)}}{\text{PWS yield (ts/tc)}}) \tag{6.1}$$

where the bio-ethanol yield is varied between 65-90 l/tc, the sugarcane yield is varied between 55-80 tc/ha, the amount of sugarcane land is fixed at 30,000 ha, the amount of PWS is varied between 100,000-130,000 ts and the PWS yield is varied between 0.07-0.12 ts/tc, see Table 5.2 and Table 6.1. The bio-ethanol production is calculated for two different amounts of PWS produced. In the first option, the PWS production equals the domestic consumption of 130,000 ts and in the second option the PWS production is reduced to about 75% of the domestic consumption, so 100,000 ts, see Table 5.2. With those two options an idea is given about the effect of the initial choice on how much PWS should be produced on the required processing yields. It is assumed that the production of bio-ethanol can start if the chosen demand of PWS is satisfied.

The results of the amount of bio-ethanol produced as calculated by Equation (6.1) are shown in Appendix C. As an example, the situation where the bio-ethanol yield equals 85 l/tc and the PWS demand is fixed at 130,000 ts is given in Figure 6.4. In the case where the PWS yield equals 0.07 ts/tc and the sugarcane yield equals 55 or 60 tc/ha, no bio-ethanol is produced. This means that in this case there is not even enough sugarcane to produce the PWS demand from, which is indicated by the red marked cells in Figure 6.4. The green marked cells in the table of Figure 6.4 indicate that with the specific combination of yields, the demand of both 130,000 tonnes of PWS and 71,000,000 liter of bio-ethanol are achieved.

Fixed		
Sugarland	30000	ha
Anhydrous bio-ethanol yield	85	l/tc
Plantation white sugar	130000	ts
Aim		
Anhydrous bio-ethanol	71000000	l

***Ethanol (l) = *10^6**

Ethanol (l)	**Sugarcane yield (tc/ha) →**					
↓ Pws yield (ts/tc)	55	60	65	70	75	80
0.07	0.00	0.00	7.89	20.64	33.39	46.14
0.08	2.13	14.88	27.63	40.38	53.13	65.88
0.09	17.47	30.22	42.97	55.72	68.47	81.22
0.1	29.75	42.50	55.25	68.00	80.75	93.50
0.11	39.80	52.55	65.30	78.05	90.80	103.55
0.12	48.17	60.92	73.67	86.42	99.17	111.92

Figure 6.4: Anhydrous bio-ethanol production as function of the plantation white sugar yield and sugarcane yield. The amount of sugarcane land and the production of plantation white sugar are set equal to 30,000 ha and 130,000 ts, respectively. The anhydrous bio-ethanol yield in this case equals 85 l/tc.

The results of the bio-ethanol production for the two different amounts of PWS produced as shown in Appendix C are discussed in detail below.

Option 1: Plantation white sugar production of 130,000 ts

In Appendix C it can be seen that the demand of both 130,000 tonnes of PWS and 71,000,000 liters of bio-ethanol cannot be achieved if the PWS yield equals 0.07-0.08 ts/tc and the sugarcane yield equals 55-60 tc/ha for a bio-ethanol yield varied between 65-90 l/tc. This is in accordance with what was stated earlier based on Figure 6.2 and Figure 6.3. Moreover, if the sugarcane yield equals 65 tc/ha the demand of PWS and bio-ethanol for this option can only be met if the industrial processing yields are equal to the maximum values of the ranges considered, so a PWS yield of 0.12 ts/tc and a bio-ethanol yield of 85-90 l/tc, see Table 6.1.

For this option, it is expected that the operation with bio-ethanol yields of 65-70 l/tc is less promising compared to the operation with higher bio-ethanol yields. This is due to the fact that the lower the bio-ethanol yield, the higher the sugarcane yield and PWS yield have to be. As described for design choice 2, the production of anhydrous bio-ethanol is new in Jamaica and thus requires the installation of equipment, see section 4.3. This equipment can be selected based on the efficiency and yield, while the increase in the sugarcane yield requires an improvement in the farming practices of both the hectares owned by the estates and by the private and subsistence farmers. In section 3.3.2 it is mentioned that the constraints for the "knowledge development and diffusion" function indicate that knowledge enhancement and transfer of knowledge from what is clear in theory to actual farming practices is requiring a lot of effort. Because of this, it is expected to be more convenient to have the factory managers having a say about installing a new bio-ethanol process that achieves high yields, instead of trying to improve the sugarcane yield of thousands hectares of sugarcane land which requires the support of many different people.

A potential combination of yields for this option is when the bio-ethanol yield equals 75 l/tc, the PWS yield equals 0.10 ts/tc and the sugarcane yield equals 75 tc/ha, see Appendix C. This combination is suggested to be more feasible compared to the combinations where the PWS yield and sugarcane yield are the same, but the bio-ethanol yield is increased, because a production of more than 71,000,000 l of bio-ethanol is considered needless without the possibility to sell it.

Another potential combination of yields where the demand of PWS and bio-ethanol are satisfied is when the bio-ethanol yield equals 80 l/tc, the PWS yield equals 0.11 ts/tc and the sugarcane yield equals 70 tc/ha, see Appendix C. An advantage of this combination compared to the aforementioned combination is the lower sugarcane yield. This lower sugarcane yield comes along with an increase in the bio-ethanol yield. However, as argued before it is expected to be more achievable to obtain higher bio-ethanol yields than higher sugarcane yields. Moreover, this combination is suggested to be more feasible compared to the combinations where the PWS yield and the sugarcane yield still equal 0.11 ts/tc and 70 tc/ha respectively, but where the bio-ethanol yield is higher than 80 l/tc as a production of more than 71 million liters of bio-ethanol is considered unnecessary as was stated before.

The combination of a bio-ethanol yield of 85 l/tc, a PWS yield of 0.12 ts/tc and a sugarcane yield of 65 tc/ha can also be considered as a potential combination, see Appendix C. However, this combination requires a relatively high bio-ethanol and PWS yield with only a relatively small increase of the sugarcane yield compared to the current situation, see Table 5.2. Still, this combination is suggested to be more feasible compared to the combination where the PWS and the sugarcane yield stays the same, but where the bio-ethanol yield equals 90 l/tc for the same reason as given earlier.

When the bio-ethanol yield equals 90 l/tc, there are two combinations of yields which can be considered for this option. One is the combination where the PWS yield equals 0.10 ts/tc and where the sugarcane yield equals 70 tc/ha. For this combination, a high bio-ethanol yield is required, which could be achieved when the equipment is selected based on this high yield and when the equipment is operated appropriately. An advantage of this combination is the relatively low PWS and sugarcane yield required. The other combination requires a PWS yield of 0.09 ts/tc and a sugarcane yield of 75 tc/ha. This combination is suggested less feasible compared to the aforementioned one as it is less desirable to increase the sugarcane yield in favor of the PWS yield due to the earlier mentioned time and effort required to improve the farming best practices.

In Table 6.2 a summary is given of the above mentioned potential combinations of yields where the production of 130,000 tonnes of plantation white sugar and 71,000,000 liters of anhydrous bio-ethanol is achieved. From those combinations, the ones where the sugarcane yield equals 70 tc/ha are suggested to be the most convenient ones as in those combinations the sugarcane yield is relatively low, while a not too high PWS yield is required. The relatively high yields of bio-ethanol can be challenging, however those yields can be achieved with the right installed equipment and a sugar content approaching the 17%, see section 5.3.1. Also the case where the sugarcane yield equals 75 tc/ha, the bio-ethanol yield equals 75 l/tc and the PWS yield equals 0.10 ts/tc is considered as one of the most feasible combinations for this option. In this case, a relatively small increase in the sugarcane and PWS yield is required compared to the current situation and the required bio-ethanol yield is relatively low compared to the considered range, see Table 5.2 and Table 6.1.

Table 6.2: Summary of potential combinations of yields where the demand of 130,000 tonnes of plantation white sugar and 71,000,000 liters of anhydrous bio-ethanol are satisfied, see option 1 in Appendix C. *Suggested as most feasible combinations for this option.

	Bio-ethanol yield (l/tc)	**PWS yield (ts/tc)**	**Sugarcane yield (tc/ha)**
*	75	0.10	75
*	80	0.11	70
	85	0.12	65
*	90	0.10	70
	90	0.09	75

Option 2: Plantation white sugar production of 100,000 ts

For this option, the PWS demand is reduced by 25% compared to the current amount consumed in Jamaica, see Table 5.2. This reduction in the amount of PWS produced results in lower processing yields required to produce the 100,000 tonnes of PWS and the 71,000,000 liters of bio-ethanol, see option 2 in Appendix C. For this second option there a no red marked cells in the tables of Appendix C, which means that the production of 100,000 tonnes of PWS is satisfied for every combination of yields. In addition, the area occupied by the green cells that indicate that the bio-ethanol demand is satisfied is significantly increased compared to option 1, see Appendix C. Due to the increased amount of combinations of yields for this option where the demand of both PWS and bio-ethanol are met, the relatively high sugarcane yields of 75-80 tc/ha, the PWS yield of 0.12 ts/tc and the bio-ethanol yield of 90 l/tc are taken out of consideration as other combinations that require lower yields are expected to be more feasible in the context as they require less effort to be achieved.

In Table 6.3 a summary is given of the potential combinations of yields where the demand of 100,000 tonnes of plantation white sugar and 71,000,000 liters of anhydrous bio-ethanol are satisfied. The combinations of yields where the PWS and sugarcane yield stay the same, while the bio-ethanol yield is increased are not considered as potential combinations, because producing more than 71 million liters of bio-ethanol is considered to be irrational in the context.

Table 6.3: Summary of potential combinations of yields where the demand of 100,000 tonnes of plantation white sugar and 71,000,000 liters of anhydrous bio-ethanol are satisfied, see option 2 in Appendix C. *Suggested as most feasible combinations for this option.

	Bio-ethanol yield (l/tc)	**PWS yield (ts/tc)**	**Sugarcane yield (tc/ha)**
*	65	0.10	70
	70	0.11	65
*	75	0.09	70
*	75	0.10	65
	80	0.11	60
	85	0.08	70
	85	0.09	65

The combination where the sugarcane yield equals 60 tc/ha is only suggested if it indeed turns out that improving the farming best practices, if only for a small improvement, requires an unfeasible amount of time and effort, see Table 6.3. If it is possible to improve the farming best practices to some extent, it is suggested to do this as this will lower the required PWS and bio-ethanol yield.

When the sugarcane yield equals the relatively low value of 65 tc/ha, there are three potential combinations of yields where the demand of PWS and bio-ethanol are satisfied for this option, see Table 6.3. For this option, a low sugarcane yield does not require significant higher values for the bio-ethanol and PWS yield as is the case in option 1. From those three combination the one where the bio-ethanol yield equals 75 l/tc and where the PWS yield equals 0.10 ts/tc is considered to be the most feasible. This combination requires a significant lower bio-ethanol yield compared to the combination where the bio-ethanol yield equals 85 l/tc and the PWS yield equals 0.09 ts/tc. Moreover, it does not require the relatively high PWS yield of 0.11 ts/tc in the case the bio-ethanol yield is 70 l/tc. As in general the costs of improving increase when the yields are getting higher, this medium combination is suggested as the most feasible option out of the three combinations.

There are also three potential combinations of yields when the sugarcane yield equals 70 tc/ha, see Table 6.3. The most feasible combination of yields is suggested to be also the medium combination that contains a bio-ethanol yield of 75 l/tc and a PWS yield of 0.09 ts/tc. However, the combination of yields where the bio-ethanol yield equals 65 l/tc and the PWS yield equals 0.10 ts/tc could also be feasible as the bio-ethanol yield is equal to the minimum value of the range considered, while the other yields are not tremendously higher compared to the current situation, see Table 5.2.

6.5.2. Energy Generation and Production of Bio-pellets from Bagasse

To study the influence of the sugarcane yield and the energy yield from bagasse on the amount of bagasse required to generate energy and the amount of bagasse available to produce bio-pellets, the amount of bio-pellets produced is calculated by the following equations:

$$\textbf{Pellets (tp)} = \text{pellet yield (tp/tb)} * (\text{bagasse (tb)} - \text{bagasse for energy (tb)}) \tag{6.2}$$

$$\text{Bagasse (tb)} = \text{bagasse yield (tb/tc)} * \text{sugarcane yield (tc/ha)} * \text{sugar land (ha)} \tag{6.3}$$

$$\text{Bagasse for energy (tb)} = \frac{\text{energy-SE (kWh)} + \text{energy-P (kWh)}}{\text{energy yield from bagasse (kWh/tb)}} \tag{6.4}$$

$$\text{Energy-SE (kWh)} = \text{energy-SE (kWh/tc)} * \text{sugarcane yield (tc/ha)} * \text{sugar land (ha)} \tag{6.5}$$

$$\text{Energy-P (kWh)} = \frac{\text{energy-P (kWh/tb)}}{\text{pellets yield (tp/tb))}} * \textbf{pellets (tp)} \tag{6.6}$$

where the bio-pellet yield is 0.5 tp/tb, the bagasse yield is 0.25 tb/tc, the sugarcane yield is varied between 55-80 tc/ha, the amount of sugarcane land is fixed at 30,000 ha, the energy yield from bagasse is varied between 100-600 kWh/tb, the energy demand for the production of plantation white sugar and anhydrous bio-ethanol (energy-SE) equals 30 kWh/tc, and the energy demand for the production of bio-pellets (energy-P) equals 740 kWh/tb, see Table 5.2 and Table 6.1.

To obtain the amount of bio-pellets that can be produced, the bagasse needed to satisfy the energy demand for processing should be known, see Equation (6.2). However, to define the energy demand for pelleting, the amount of bio-pellets produced should be known, see Equation (6.6). To solve this self-dependency problem, the amount of bio-pellets produced in Equation (6.6) is fixed by an initial choice. The initial choice is defined to be between 0-100,000 tonnes of bio-pellets. This range is covered by six options with steps of 20,000 tonnes of bio-pellets. For every option, the bio-pellet production taking into account the energy demand of the fixed amount of bio-pellets, is calculated by Equation (6.2).

The results of the amount of bio-pellets produced for the six different options as calculated by Equations (6.2) to (6.6) are shown in Appendix D. It is assumed that the production of bio-pellets can start if the energy demand for processing is satisfied by the energy generation from bagasse. The red marked cells in the tables of Appendix D indicate that with the specific combination of yields there is not enough bagasse to satisfy the energy demand for processing. The green marked cells in the tables of Appendix D indicate that with the specific combination of the sugarcane and energy yield, both the energy demand for processing (including the energy demand of the fixed amount of bio-pellets produced) and the production of the set amount of bio-pellets can be achieved.

The results in Appendix D show that with an energy yield of 100 kWh/tb, the energy demand for processing cannot be achieved independent of the amount of bio-pellets produced. In other words, the production of plantation white sugar and bio-ethanol from sugarcane requires more energy than can be generated from the bagasse from this sugarcane if the energy yield equals 100 kWh/tb.

The option where the amount of bio-pellets produced is fixed at 0 tp shows the amount of bio-pellets that can be produced if the energy demand for pelleting is not covered by the energy generated from bagasse. In this case, the maximum amount of bio-pellets that can be produced equals 240,000 tp, assuming that the sugarcane yield equals 80 tc/ha and the energy yield equals 600 kWh/tb. However, if the energy of pelleting is taken into account, which is shown by the other options where the bio-pellet production is set non-zero, the amount of bio-pellets that can be produced decreases. The higher the fixed amount of bio-pellets produced, the higher the energy yield has to be and the lower the amount of bio-pellets that can be produced. This is displayed in the tables of Appendix D by an increase in red marked cells and a decrease in green marked cells upon increasing the fixed amount of bio-pellets produced.

In Table 6.4 the most feasible combination of the sugarcane yield and energy yield for every fixed amount of bio-pellets where the energy demand for processing is satisfied is summarized, see Appendix D. The most feasible combinations are based on the combination of yields which requires the lowest yields and where the production of bio-pellets is as close as possible to the fixed amount of bio-pellets produced.

Table 6.4: Summary of most feasible combinations of yields for every fixed amount of bio-pellets where the energy demand for processing is satisfied, see Appendix D.

Fixed amount of bio-pellets (tp)	**Energy yield (kWh/tb)**	**Sugarcane yield (tc/ha)**
20,000	200	65
40,000	300	65
60,000	400	65
80,000	500	70
100,000	600	75

From Table 6.4 it follows that the relatively high sugarcane yield of 80 tc/ha is not considered in one of the most feasible combinations. Moreover, the relative low sugarcane yields of 55-60 tc/ha are also not considered. This is due to the fact that if the sugarcane yield is decreased while the fixed amount of bio-pellets stays the same, the energy yield have to be increased. For example, if for a fixed bio-pellet production of 20,000 tp the sugarcane yield is lowered from 65 tc/ha to 60 tc/ha, then the energy yield has to be increased from 200 kWh/tb to 300 kWh/tb, see Appendix D. With this energy yield of 300 kWh/tb and a sugarcane yield of 65 tc/ha also 40,000 tp could have been produced, see Appendix D.

For the options where the fixed amount of bio-pellets are equal to 80,000-100,000 tp, relatively high energy yields of 500-600 kWh/tb are required to satisfy both the energy demand for processing and the fixed amount of bio-pellets, see Table 6.4. Those energy yields can be achieved if the moisture content in bagasse is approaching the 45% and if the boiler operates with high pressure and temperature resulting in a high system efficiency. However, if the installed equipment is selected based on achieving high efficiency it is of essence that the energy generation process is operated appropriately to actually be able to achieve the desired high energy yield.

6.6. Overview of Potential Yields of the Process Variables

As described in the beginning of this chapter a BFD represents the main processing sections in functional blocks and indicates the overall material balances. In this chapter, it was aimed to define the material balances for the main processes in the proposed process design as given in Figure 6.1. For this, the values of the process constants and the ranges for the yields of the process variables were defined and the influence of the process variables on the material balances was studied.

It was found that not one optimal set of yields can be pointed out as the process variables are largely dependent on four initial choices:

1. The amount of plantation white sugar produced
2. The amount of anhydrous bio-ethanol produced
3. The coverage of the energy demand for processing
4. The amount of bio-pellets produced

These choices are mainly dependent on the decisions made by the companies that currently dominate the sugar, bio-ethanol and energy trade, by the government of Jamaica and by the other actors in the Jamaican sugar sector. With the sensitivity analysis a more narrowed range for the yields of the process variables could be defined and an idea is given about the influence of the choices on the required processing yields, see Appendix C and Appendix D.

Table 6.5 shows the initial considered ranges for the yields of the process variables as given in Table 6.1 and the more narrowed ranges following from the combinations of yields suggested as the most feasible according to the sensitivity analysis, see Table 6.2, Table 6.3 and Table 6.4.

Table 6.5: Overview of the yield ranges of the process variables. The data for the initial range is from Table 6.1, the data for PWS = 130,000 is from Table 6.2, the data for PWS = 100,000 is from Table 6.3, and the data for production of bio-pellets is from Table 6.4. The numbers between brackets refer to the proposed context-specific conceptual process design in Figure 6.1.

	Initial	**PWS = 130,000 ts**	**PWS = 100,000 ts**	**Bio-pellets**	*Unit*
Process variables					
Sugarcane yield (1)	55-80	70-75	65-70	65-75	tc/ha
PWS yield (2)	0.07-0.12	0.10-0.11	0.09-0.10	-	ts/tc
Bio-ethanol yield (3)	65-90	75-90	65-75	-	l/tc
Energy yield (4)	100-600	-	-	200-600	kWh/tb

From Table 6.5 it follows that the current processing yields have to be optimized to be able to satisfy the domestic consumption of 130,000 tonnes of sugar and 71,000,000 liters of anhydrous bio-ethanol. The sugarcane yield, which is currently about 60 tc/ha, has to be increased to 70 tc/ha and the sugar yield, which is currently about 0.08 ts/tc, has to be increased to 0.10 ts/tc. If possible, the sugarcane yield can be increased up to 75 tc/ha and/or the PWS yield can be increased up to 0.11 ts/tc, which will result in lower yields required for the other processing variables. Regarding the bio-ethanol yield, it is suggested to install and well-operate fermentors that can approach bio-ethanol yields of 75 l/tc or higher. The higher the bio-ethanol yield, the lower the yield of the other process variables can be.

Table 6.5 also shows the differences in the ranges of the yields for the process variables between a PWS production of 130,000 and 100,000 ts. Both the sugarcane yield and PWS yield range are shifted to lower values. For example, the minimum required sugarcane yield for a production of 130,000 tonnes of PWS equals 70 tc/ha, while for the production of 100,000 tonnes of PWS a minimum sugarcane yield of 65 tc/ha is required. The effect of a bio-ethanol production less than 71 million liters on the required yields of the process variables is not directly shown in Table 6.5, but can be extracted from Appendix C. For both a reduction in the production of PWS and bio-ethanol, the required yields of the process variables are reduced. This shows again the dependency of the yields of the process variables on the choices on what to produce in which quantity.

The bio-pellet production is mainly dependent on the energy yield and on the choice about how much of the energy required for the processes needs to be covered by energy generation out of bagasse and which amount of bio-pellets should be produced. In the calculations to study the amount of bio-pellets that can be produced, all the energy required is covered by the energy generation from bagasse, see Appendix D. However, it is obvious to state that if energy generation is partly facilitated by using fossil fuels, there will be more bagasse available to produce bio-pellets from. Therefore, a trade-off has to be made between producing bio-pellets and providing the energy required by the processes. Only with relatively high energy yields, both a large amount of bio-pellets can be produced and the energy demand can be covered, see Table 6.4. A high energy yield can be achieved if the moisture content of the bagasse is about 45% and if with the installed equipment high efficiencies can be obtained, see section 5.3.3.

7

Financial Overview

This chapter describes the sales revenues, the market prices, the market volumes, the operational costs and capital investments related to the products and processes as proposed in the context-specific conceptual process design. With the overview of the cash inflow, cash outflow and total initial investments cost, the net present value (NPV) is determined for the production of bio-ethanol and bio-pellets in the Jamaican sugar industry. The NPV is a measurement of profitability and therefore gives some insight in the financial viability of the production of bio-ethanol and bio-pellets [132].

7.1. Sales Revenue

In this section, the maximum sales revenue per year for the Jamaican sugar industry is estimated based on the market prices and the maximum sales volumes of plantation white sugar (PWS), anhydrous bio-ethanol and bio-pellets.

7.1.1. Market Price

Table 7.1 shows the market prices of PWS, anhydrous bio-ethanol and bio-pellets, which are the products that are produced as proposed in the conceptual process design. The trade of electricity is not considered, because all the energy generated from bagasse is only used internally to satisfy the energy demand of the processes. Any excess bagasse will not be used to generate a surplus of electricity but to produce bio-pellets.

In Table 7.1 it can be seen that the market price of PWS is set equal to the market price of raw sugar. Unfortunately, a more accurate price of PWS could not be obtained from the sugar industry and an online search. This is probably due to the fact that PWS is not a very common type of sugar and that trade agreements are often secret. The price range of the bio-pellets is based on an estimate of Viride Sustra B.V. and their partners. A more accurate price of bio-pellets could not be obtained as the pellet trade from biomass-rich but still developing countries to the developed countries all over the world is not yet an established market. In addition, the production costs will be different for the various kinds of biomass due to difference in for example harvesting and moisture content, this will result in varying prices for the bio-pellets.

Table 7.1: Market prices related to the sugar sector in 2018. *Viride Sustra B.V. is a partner of the IBIS project.

		Unit	*Source*
Market price			
Plantation white sugar	12	US$/ts	*as raw sugar, see Table 5.1*
Anhydrous bio-ethanol	0.52	US$/l	[61, 107, 108]
Bio-pellets	60-80	US$/tp	Viride Sustra B.V.*

7.1.2. Maximum Sales Volume

Table 7.2 contains the maximum sales volumes and sales revenues for plantation white sugar and anhydrous bio-ethanol. The maximum sales volumes are based on the domestic consumption in Jamaica, where it is assumed that PWS is replacing the domestic consumption of raw and refined sugar, see Table 5.2. The maximum sales revenue is calculated by multiplying the maximum sales volume with the market price as given in Table 7.1 [132].

Table 7.2 also contains the maximum sales volume and sales revenue of bio-pellets from bagasse. The maximum sales volume of bio-pellets is limited by the amount of bagasse available and thereby dependent on the sugarcane yield and energy yield. The sugarcane yield required to obtain the maximum sales volumes of PWS and bio-ethanol is suggested to be 70-75 tc/ha, see Table 6.5. With a sugarcane yield of 75 tc/ha and the maximum energy yield considered in this thesis (600 kWh/tb) about 100,000 tonnes of bio-pellets can be produced, see Table 6.4.

Table 7.2: Maximum sales volume and sales revenue related to the sugar sector in 2018.

	Sales volume	**Sales revenue**
Plantation white sugar	130,000 ts/year	1.65 million US$/year
Anhydrous bio-ethanol	71,000,000 l/year	36.92 million US$/year
Bio-pellets	100,000 tp/year	6-8 million US$/year

As mentioned in section 6.5.1, the established import markets of sugar and bio-ethanol in Jamaica have an influence on the amount that can be domestically produced. On the one sight, the established market is a strong competitor of the domestic production and may force a reduction in the maximum sales volumes. Consequently, the sales revenues will also go down as the possibility to sell the products cannot be guaranteed. On the other sight, the established import market allows a reduction in the domestic production if the required farming and industrial processing yields cannot be achieved. The influences of a reduction in the amount of PWS and bio-ethanol produced on the required processing yields are shown in Appendix C and described in more detail in section 6.5.

The maximum sales volume of 100,000 tonnes of bio-pellets requires a relatively high energy yield of 600 kWh/tb. If this energy yield cannot be achieved the sales volume and consequently, the sales revenue will reduce significantly, see Table 6.4.

7.2. Capital and Operational Expenditures

In this section, literature data is given about the capital expenditures (CAPEX), operational expenditures (OPEX) and total production costs (TPC) required in the processes that are proposed in the conceptual process design. The processes included in the proposed process design are the sugarcane juice extraction in the sugar mill, the production of plantation white sugar in the refinery, the bio-ethanol fermentation, the energy generation from bagasse, and the pelleting of bagasse, see the conceptual process design in Figure 4.5. However, in this section only the CAPEX, OPEX and TPC of the bio-ethanol fermentation process and the production of bio-pellets are described in detail as those processes are new in the Jamaican sugar industry and thus require the installation and operation of new equipment of which the costs have to be identified.

By summing up the operation and capital expenses, the total costs of production in US$/year or in US$ per amount of product produced can be determined [132]. To be able to convert a CAPEX given in US$, to the capital charge per amount of product annually produced given in US$/amount, the following equation is used:

$$\text{Capital charge (US\$/amount)} = \frac{\text{CAPEX (US\$)}}{\text{capacity (amount/year)}} * \frac{\text{i}}{1-(1+i)^{-y}} \tag{7.1}$$

where i is the discount rate and where y is the plant life time. In this thesis a discount rate of 7% and a plant life time of 20 years are assumed.

A detailed cost analysis on the sugarcane juice extraction in the sugar mill, the production of plantation white sugar and the energy generation in the Jamaican factories is thus not given in this thesis. Unfortunately, the financial data about the production of sugarcane and the processing of sugarcane into raw sugar could not be obtained from the Jamaican sugar industry due to a lack of communication. The CAPEX and OPEX are also not extracted from literature as considering a total CAPEX for a situation where the factories are out their already is irrational and as the OPEX is expected to differ significantly based on the scale and proficiency. In addition, detailed knowledge of the factories is necessary to assess the investments required to upgrade and improve the existing factories.

Regarding the production of PWS, it is assumed that the extra clarification step required in the processing of sugarcane into PWS instead of raw sugar, is balanced by the increased sales price of PWS in comparison with the sales price of raw sugar. Due to the fact that the sales price of raw sugar and PWS are set the same as given in Table 7.1, no investments and extra operational costs for the production of PWS compared to raw sugar are considered in this thesis.

The third design choice is about generating heat and energy through combustion of bagasse in boilers, this requires the installation and operation of high efficiency steam turbines and steam driven mills to be able to satisfy the energy demand of the other processes in the design, see section 4.4. Unfortunately, the boilers currently installed in the Jamaican sugar factories were designed to maximize the amount of bagasse used and therefore they have low efficiencies [46]. The financial data of the installed boilers and the energy yield from bagasse was also not available from the Jamaican sugar factories. Literature data on the energy yield from bagasse is given in section 5.3.3. The capital and operational expenses for co-generation from bagasse reported in literature are often included in the CAPEX and OPEX for bio-ethanol production from sugarcane. For example, the CAPEX of steam and electricity generation in a combined heat and power plant (22 bar) for an annexed and an autonomous distillery, where bio-ethanol is produced from sugarcane, are reported in a study to be 39.3 million US$ and 39.7 million US$, respectively [133]. Another study reports that about 54 million US$ of the total CAPEX of 180 US$ for a conventional autonomous bio-ethanol distillery, was required for the co-generation with boilers operating at 22 bar [134]. In the same order, but a bit lower compared to the aforementioned required investments, another study reports a CAPEX of 12 million US$ for a boiler operating at 63 bar [86]. In this thesis, the CAPEX and OPEX considered for the anhydrous bio-ethanol production from sugarcane via fermentation in Jamaica will also include the CAPEX and OPEX for the energy generation from bagasse, therefore this will not be accounted separately. For this, it is assumed that an increase in capacity of the boilers due to the demand of energy in the PWS production and pelleting on top of the demand for bio-ethanol fermentation, will not significantly increase the CAPEX and OPEX of the energy generation process due to the economies of scale [132].

7.2.1. Bio-ethanol Fermentation

The second design choice is about the production of anhydrous bio-ethanol from sugarcane via fermentation, see section 4.4. The production of bio-ethanol requires the implementation and operation of processes which are new to Jamaica. In a study about first-generation bio-ethanol production in the Jamaican sugar sector, the investment required to integrate the production of anhydrous bio-ethanol to the existing sugar factories in Jamaica is reported to be 146 million US$ for the period between 2018-2021 and 183 million US$ for the period from 2022 until 2030 [61]. In this study an annual bio-ethanol production of 75 million liter is considered and it is expected that the investments required after 2030 can be covered with the revenues. From the estimated investments and the capacity, the capital charge in US$/l is calculated for the different time periods mentioned, see Table 7.3.

To compare the values estimated in the study about the bio-ethanol production Jamaica, Table 7.3 also shows the plant capacity, the CAPEX in US$ and in US$/l, and the OPEX as reported in several other studies. All the data given in Table 7.3 consider the bio-ethanol production from sugarcane via fermentation, except one study which reports the bio-ethanol production from sugarcane juice in the USA.

Table 7.3: Capital and operational expenditures of bio-ethanol production from sugarcane via fermentation. *Calculated with eq. (7.1). **Bio-ethanol is produced from sugarcane juice instead of sugarcane.

	Capacity *(million l/year)*	**CAPEX** *(US$)*	**CAPEX** *(US$/l)*	**OPEX** *(US$/l)*	*Source*
Country					
Jamaica (2018-2021)	75	146	0.74*	-	[61]
Jamaica (2022-2030)	75	183	0.41*	-	[61]
Jamaica (2018-2030)	75	329	0.55*	-	[61]
South Africa	201	372	0.17*	0.10	[126]
Brazil	170	188.9	0.10*	0.40	[135]
Brazil	164	180	0.10*	0.37	[134]
Brazil	-	-	-	0.55	[54]
Brazil	170	87.64	0.05*	0.34	[136]
Brazil	-	-	-	0.26	[52]
USA	-	-	-	0.57	[52]
USA - subsidies	-	-	-	1.11	[52]
Brazil	-	-	-	0.21	[109]
USA	-	-	-	0.63	[109]
USA	75	157.5	0.20	-	[109]
USA	150	244.5	0.16	-	[109]
USA**	75	101.25	0.13	-	[109]
USA**	150	157.5	0.10	-	[109]

The study analyzing the economic feasibility of ethanol production from sugarcane and sugarcane juice in the USA reports the CAPEX for plant capacities of 75 and 150 million liter bio-ethanol per year, see Table 7.3. For both the bio-ethanol production from sugarcane and sugarcane juice the investment required per liter decreases upon increasing the total production capacity, which is a result of the economies of scale [132]. From Table 7.3, the CAPEX accounting for the processing of sugarcane into sugarcane juice can be extracted from the difference between the data given for bio-ethanol production from sugarcane and from sugarcane juice. For a bio-ethanol plant with a capacity of 75 million l/year a capital charge of 0.04 US$/l is required to convert the sugarcane into sugarcane juice, while a 150 million l/year plant requires for this a capital charge of 0.03 US$/l.

The capital charges given for the production of 75-150 million liters of bio-ethanol from sugarcane and sugarcane juice in the USA are between 0.10-0.20 US$/l, see Table 7.3. The results from this study are in the same range as the CAPEX of 0.10 reported in two studies about bio-ethanol production in Brazil [134, 135] and the CAPEX of 0.17 reported in the study describing the economic analysis of bio-ethanol and electricity production from sugarcane in South Africa [126], see Table 7.3. The only value that differs slightly from the other data obtained is the relatively low capital charge of 0.05 US$/l, which is reported in a study about the economics of current and future biofuels in Brazil [136].

In the study considering a conventional autonomous distillery with a capacity of 164 million l/year, a CAPEX of 180 million US$ was reported, which is based on information from the major equipment manufacturers for the bio-ethanol industry in Brazil [134]. It is mentioned that from this total CAPEX, 27 million US$ is required for sugarcane juice extraction, 31 million US$ is required for the sugarcane juice treatment, fermentation and distillation, and 54 million US$ is required for co-generation [134]. The study that reports a CAPEX of 188.9 million US$ also considers a conventional autonomous distillery including co-generation [135]. This CAPEX was obtained from the model of Virtual Sugarcane Biorefinery that has been developed by the Brazilian Bio-ethanol Science and Technology Laboratory.

The study describing the economic analysis of bio-ethanol and electricity production from sugarcane in South Africa reports a CAPEX of 372 million US$ for an autonomous distillery with a capacity of 200 million liter bio-ethanol per year. In the study, it is mentioned that the CAPEX is based on vendor quotes in South Africa, which results in a CAPEX estimate that is relatively high and not competitive internationally. Despite the fact that the capital charge of 0.17 US$/l for this distillery in South Africa does not significantly differ from the other studies, the message that South Africa cannot be compared one on one with Brazil and the USA should be taken into account by estimating the CAPEX required for a bio-pellet plant in Jamaica. Due to the fact that the bio-ethanol production is new in Jamaica and that the current sugar industry is low-tech and not very efficient it is not surprising that the CAPEX for a bio-ethanol plant in Jamaica is higher in comparison with such a project in Brazil and the USA. Moreover, the inclusion of co-generation will significantly increase the total CAPEX. Therefore, a relatively high CAPEX of 0.50 US$/l is considered in this thesis for the integration of a bio-ethanol plant and a co-generation plant with a life time of 20 years into the existing Jamaican sugar industry.

The values of the OPEX given for the bio-ethanol production in the USA equal 0.57 and 0.63 US$/l, see Table 7.3. A remarkable fact reported in one of the studies about bio-ethanol production in the USA is that if the production cost of a liter of bio-ethanol are added to the tax subsidy cost, the total cost for a liter of bio-ethanol would be US$1.11. Regarding the bio-ethanol production in Brazil, the OPEX values given for the production of bio-ethanol from sugarcane via fermentation are between 0.21-0.40 US$/l with one exception where the OPEX equals 0.55 US$/l, see Table 7.3. A possible reason for the higher OPEX of 0.55 US$/l is that this OPEX includes the operating expenses of the sugarcane production and the cost of the sugar land [54]. The difference in OPEX between the USA and Brazil is probably due to the relatively low feedstock cost of sugarcane in Brazil [109]. The reason that the OPEX of 0.10 US$/l given for the bio-ethanol production in South Africa is significantly lower in comparison to the values reported for Brazil and the USA, is that this OPEX does not consider the cost of the raw materials, the power and the maintenance. All OPEX values given in Table 7.3 include the energy generation from bagasse.

In literature, no estimations of the OPEX for the production of bio-ethanol from sugarcane in Jamaica were found. It is assumed that the OPEX in Jamaica will be higher than the values reported in the literature for Brazil. The main reason for this is that the bio-ethanol production in Brazil is an established industry, while it is new to Jamaica. However, as sugarcane in Jamaica is abundant and relatively cheap, it is assumed that the OPEX in Jamaica will not be significantly higher than the values reported in literature for the USA. Therefore, the OPEX of the anhydrous bio-ethanol production from sugarcane via fermentation in the Jamaican sugar industry is considered to be 0.55 US$/l in this thesis.

Concluding, the CAPEX and OPEX considered in this thesis for the production of 71 million liters of anhydrous bio-ethanol from sugarcane via fermentation including the co-generation from bagasse are 0.50 US$/l and 0.55 US$/l, respectively. Based on the annual production of 71 million liter of bio-ethanol and eq. (7.1), the CAPEX becomes about 376 US$ or 35.5 million US$/year and the OPEX becomes 39.1 million US$/year. From this the TPC of anhydrous bio-ethanol production from sugarcane via fermentation including co-generation from bagasse in Jamaica equals 74.6 million US$/year or 1.05 US$/l.

7.2.2. Pellet Technology

Design choice 4 proposes the integration of a pellet plant into the existing sugar factories in Jamaica. In this thesis, the process to make bio-pellets from bagasse includes chipping, drying, pelleting, cooling and storage. Thus, no costly pretreatment steps are considered that would increase the total CAPEX and OPEX significantly, [100]. Table 7.4 contains an overview of the CAPEX, OPEX and TPC reported in literature for the production of bio-pellets from various types of biomass.

The financial data obtained from the literature match each other quite well, see Table 7.4. The CAPEX values obtained for a pellet plant with a capacity of at least 35,000 tp are between 6 US$/tp and 17.4 US$/tp. The OPEX values obtained for a pellet plant with a capacity of about 40,000 tp are between 45 US$/tp and 60 US$/tp. The most remarkable exception is the very high TPC reported for straw pellets in the study about the development of agri-pellets, see Table 7.4. This is partly due to the fact that this study includes a detailed cost analysis on the transportation of the biomass from the field to the land. In this study, it is reported that the transportation alone contributes almost 40% of the total cost [114]. It should be noted that, unless the values in this study are significantly higher compared to other studies in literature, it is used as basis in a study performing a techno-economic analysis of the extension of the bio-pellet production with steam explosion as pretreatment [100].

Table 7.4: Capital expenditures (CAPEX), operational expenditures OPEX), and total production costs (TPC) of the production of bio-pellets. *Assuming 7,500 operating hours in a year. **Calculated with Equation (7.1) based on a of CAPEX of 2-3 million US$ as reported in this study.

	Capacity *(tp/year)*	**Moisture content** *(%)*	**CAPEX** *(US$/tp)*	**OPEX** *(US$/tp)*	**TPC** *(US$/tp)*	*Source*
Biomass type						
Wood	37,500*	40	10	50-60	-	[128]
Not specified	45,000	40	6	45	51	[137]
Not specified	75,000	40	-	-	40	[137]
Switchgrass	80,000	20	17.4	-	39.4	[129]
Straw	25,000	14	-	-	230	[114]
Straw	150,000	14	-	-	130	[114]
Salix	80	30	109	-	306	[138]
Salix	800	30	56	-	123	[138]
Salix	8,000	30	23	-	64	[138]
Salix	80,000	30	10	-	47	[138]
Bagasse	12,000	50	15.7-23.6**	-	-	[131]

From Table 7.4, it can be seen that the cost of the bio-pellet production reduces up on increasing the plant capacity. This is shown in detail in the study about the bio-pellet production from salix, where the CAPEX and TPC are given for a plant capacity ranging from 80 till 80,000 tp/year. In general, the small-scale pellet plants of 800 tp/year and less are more expensive to operate compared to larger plants, which eventually increases the total production cost [137, 138].

Concluding, the CAPEX and OPEX considered in this thesis for the production of bio-pellets from bagasse in the Jamaican sugar industry are 10 US$/tp and 50 US$/tp, respectively. Based on the maximum sales volume of 100,000 tonnes of bio-pellets and eq. (7.1), the CAPEX becomes about 10.6 million US$ or 1.0 million US$/year and the OPEX becomes 5.0 million US$/year. From this the TPC of the bio-pellet production from bagasse in the Jamaican sugar sector equals 6.0 million US$/year or 6 US$/tp. For this, it is assumed that all the surplus bagasse in the Jamaican sugar industry is transported to one pelleting plant with a capacity of 100,000 tp. It can be questioned if it is more convenient to integrate a pellet plant into each of the 5 sugar factories currently in operation in Jamaica, to avoid transportation. The CAPEX and OPEX for a bio-pellet plant with a capacity of 20,000 tp are considered to be 20 US$/tp and 60 US$/tp, respectively.

7.3. Financial Appraisal

The profitability of the bio-ethanol and bio-pellet production in Jamaica are determined by calculating the net present value (NPV) from the cash inflows and outflows over a period of time with the following equation:

$$\text{NPV (US\$)} = (revenue(US\$/year) - OPEX(US\$/year)) * \frac{1-(1+i)^{-n}}{i} - CAPEX(US\$) \tag{7.2}$$

where n is the number of time periods and i is the discount rate [132]. In this thesis, a maximum number of time periods of 20 years and a discount rate of 7% are assumed. The revenue, OPEX and CAPEX are as suggested in the previous sections.

7.3.1. Bio-ethanol Fermentation

In Table 7.1, the NPV for the bio-ethanol production from sugarcane via fermentation including co-generation is shown for a bio-ethanol plant with an annual capacity of 71 million liters and a time period of 20 years. The base case considers a CAPEX of 0.50 US$/l and an OPEX of 0.55 US$/l as was proposed in section 7.2 and a revenue based on the market price of 0.52 US$/l as given in Table 7.1. This base case results in a negative NPV due to the fact that the operational cost per year are higher than the revenue, showing that this project results in a net loss and will not generate any profit. If the OPEX is decreased to for example 0.2 US$/l, the NPV is less negative but still the total costs exceed the revenue.

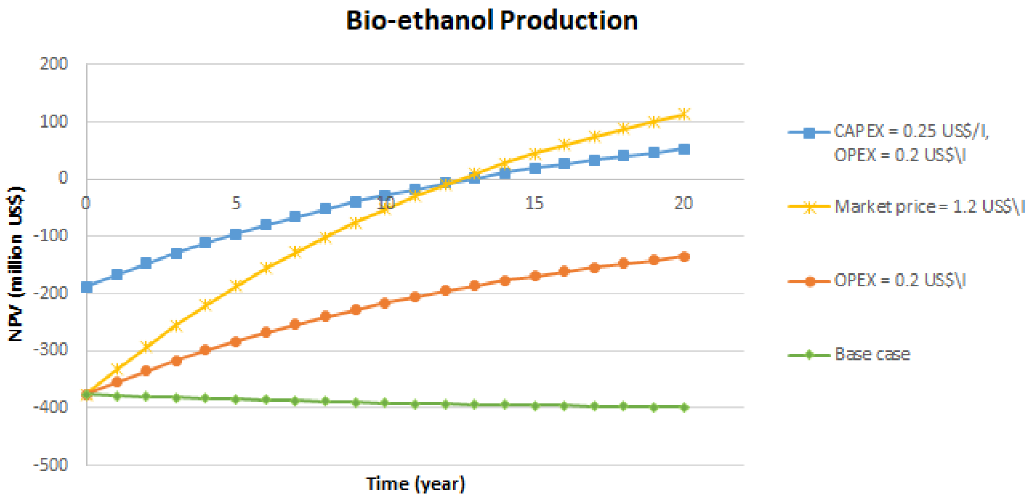

Figure 7.1: Net present value (NPV) for the bio-ethanol production from sugarcane via fermentation including co-generation, where the bio-ethanol plant has an annual capacity of 71 million liters. The base case considers a CAPEX of 0.50 US$/l, an OPEX of 0.55 US$/l and a revenue based on the market price of 0.52 US$/l.

Table 7.1 shows only two cases where the bio-ethanol production can be profitable. In one case the market price is increased from 0.52 US$/l to 1.2 US$/l, while keeping the CAPEX and OPEX as in the base case. This results in a payback period of about 12 years, after which the NPV is positive and profit is made. As described in section 4.3, the domestically produced bio-ethanol has to compete with the price of imported bio-ethanol to guarantee the possibility to sell it. This means, that the price increase of 0.68 US$/l cannot be settled on the customers, but should be covered by fundings or subsidies. Here, the government of Jamaica has to play a role with the aim to support diversification to keep the Jamaican sugar industry alive and establish the sustainable bio-based economy. Decreasing the market price of bio-ethanol by raising subsidies is rather common than exceptional as was shown by the study reporting a total cost of 1.11 US$/l for bio-ethanol production in the USA [52].

The other case where the bio-ethanol production can be profitable also shows a payback period of about 12 years. However, in this case the CAPEX and OPEX are tremendously reduced to 0.25 US$/l and 0.2 US$/l, respectively. In this case, the market price is the same as in the base case, so 0.52 US$/l. A simultaneous decrease in both the CAPEX and OPEX is unrealistic in Jamaica as lower operational expenses require process improvements or even new machinery, which results in an increase in the CAPEX. However, some reduction of the OPEX can be possible in the future if the processes are operated more efficiently and if the knowledge and proficiency of the process are developed. However, the very low CAPEX and OPEX of 0.25 US$/l and 0.2 US$/l, respectively, are not considered realistic for the bio-ethanol production in the Jamaican sugar industry. Moreover, although such a low CAPEX and OPEX can be realistic for the more experienced bio-ethanol producing countries like Brazil, still hardly any profit can be made in this case which suggests that also in those countries the bio-ethanol production is heavily subsidized.

7.3.2. Pellet Technology

In Table 7.2 and Table 7.3, the NPV for the bio-pellet production from bagasse is shown for a bio-pellet plant with an annual capacity of 100,000 tp and 20,000 tp, respectively. The NPV for a bio-pellet plant with a capacity of 100,000 tp/year is based on a CAPEX of 10 US$/tp and an OPEX of 50 US$/tp, while the NPV for a bio-pellet plant with a capacity of 20,000 tp/year is based on a CAPEX of 20 US$/tp and an OPEX of 60 US$/tp as was suggested in section 7.2. The revenue is the same for both capacities and is based on the market price range of 60-80 US$/tp as given in Table 7.1.

Table 7.2 shows that if the market price is equal to 60 US$/tp, a positive NPV will not be reached in 20 years. As result of this no profits are made, due to the fact that the costs are not exceeded by the earnings. However, if the market price for bio-pellets equals 70 US$/tp or 80 US$/tp, profit is generated after the payback period of 7 years and 4 years, respectively, see Table 7.2.

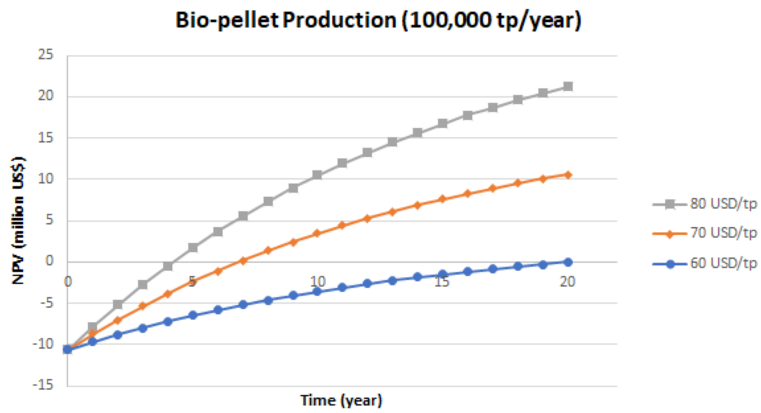

Figure 7.2: Net present value (NPV) for the bio-pellet production from bagasse, where the bio-pellet plant has an annual capacity of 100,000 tp. The CAPEX equals 10 US$/tp and the OPEX equals 50 US$/tp.

Table 7.3 shows that for a market price equal to or less than 80 US$/tp, the NPV will not be positive in the first 20 years. If the market price for bio-pellets is increased up to 90 US$/tp, while the CAPEX and OPEX stay the same as in the other cases, the payback period is about 10 years, see Table 7.3. This indicates that if the bio-pellet production is decentralized at the five operating sugar factories in Jamaica, some subsidy is required and/or the production costs have to be decreased to reduce the market price while still profit can be made.

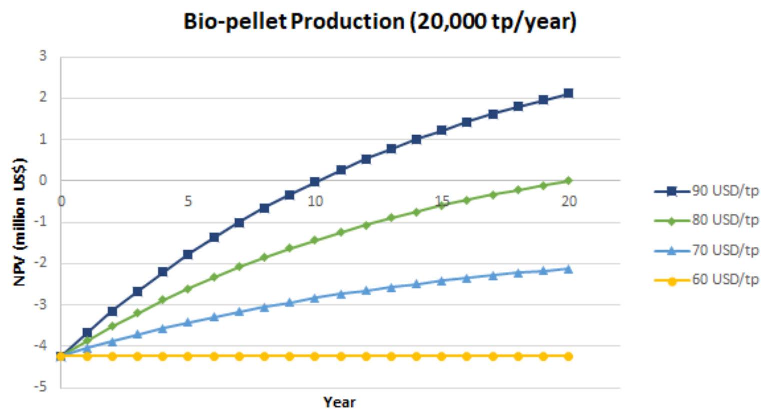

Figure 7.3: Net present value (NPV) for the bio-pellet production from bagasse, where the bio-pellet plant has an annual capacity of 20,000 tp. The CAPEX equals 20 US$/tp and the OPEX equals 60 US$/tp.

8

Discussion

In this chapter, all the information obtained in the previous chapters is combined. Three scenarios of the proposed context-specific conceptual design for the Jamaican sugar industry are discussed including the design choices, material balances, financial viability and the possible implications of the proposed design in the context.

8.1. Choice of Scenarios

The first scenario reflects the status quo of the sugar industry in Jamaica. This scenario suggests what will happen and what will not happen in the Jamaican sugar sector if everything stays the same as it is now. The outcomes and expectations of this "status-quo" scenario will be compared with two other scenarios to see if the changes made in the other scenarios are promising to revitalize the Jamaican sugar sector and to support the self-sufficient sustainable bio-based economy in Jamaica. The second scenario gives the technically ideal option of the conceptual process design and the third scenario suggests the most realistic option as considered in this thesis. The difference in outcomes and expectations between the "technical-ideal" scenario and the "most-realistic" scenario will indicate the influence of taking into account the context in the development of a conceptual process design. Figure 8.1 displays the three scenarios in a scenario matrix where the vertical axis represents the amount of different products made and the horizontal axis represents the amount of places where the products are produced. Diversification is one of the key principles of the bio-refinery concept and is considered to be a measurement for the establishment of a sustainable bio-based economy. The amount of production sites is considered to be a measurement as to what extent the scenario is integrated into the current context.

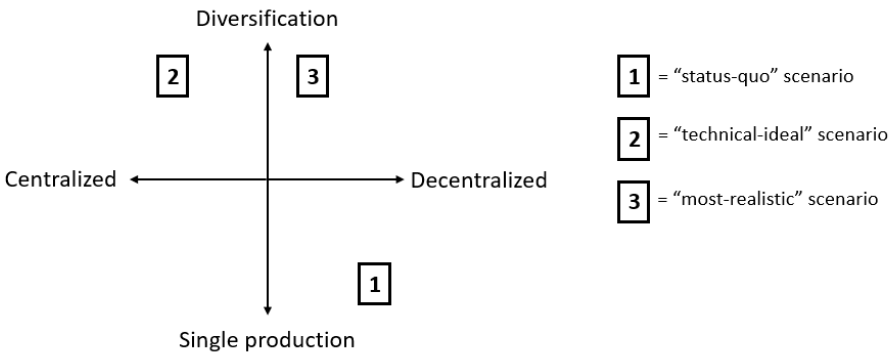

Figure 8.1: Scenario matrix showing the 1) "status-quo" scenario, 2) "technical-ideal" scenario, and the 3) "most-realistic" scenario. The vertical axis represents the amount of different products made and the horizontal axis represents the amount of places where the products are produced.

8.2. First Scenario - Status Quo

8.2.1. Design Choices

Table 8.1 shows the process constants, process variables and production demand for a scenario based on the status quo in the Jamaican sugar industry. The amount of sugarcane land, the sugarcane yield and the raw sugar yield are based on the harvest season 2016/2017 in the Jamaican sugar industry, see Table 5.2. The bagasse yield and energy demand for the production of raw sugar are based on data obtained from literature, see Table 6.1. The energy yield of 100 kWh/tb is based on bagasse with a moisture content of 55% moisture and boilers operating at about 5% efficiency, see Table 5.4. This low energy yield of 100 kWh/tb could be possible in the current low-tech and not very efficient sugar industry of Jamaica, see section 5.3.3.

The demand for raw sugar in this scenario is equal to 60,000 ts, which is in accordance with the consumption of raw sugar in Jamaica, see Table 5.2. The export of raw sugar is not considered in this "status-quo" scenario, because the export market is expected to decline tremendously. This is due to the fact that the Jamaican sugar industry cannot compete with the world market prices of raw sugar. The energy demand required in the production of raw sugar is equal to 54,000,000 kWh (= 60 tc/ha * 30,000 ha * 30 kWh/tc). For this, it assumed that all the sugarcane harvested is processed into raw sugar.

Table 8.1: The process constants, process variables and production demand for a scenario based on the status quo in the Jamaican sugar industry 2018.

		Unit
Process constants		
Sugarcane land	30,000	ha
Bagasse yield	0.25	tb/tc
Energy demand for processing	30	kWh/tc
Process variables		
Sugarcane yield	60	tc/ha
Raw sugar yield	0.08	ts/tc
Energy yield	100	kWh/tb
Production demand		
Raw sugar	60,000	ts
Energy	54,000,000	kWh

The production of plantation white sugar, anhydrous bio-ethanol and bio-pellets is not considered in this "status-quo" scenario as the extra clarification step for the production of PWS, the fermentation plant and the pellet technology do not currently exist in Jamaica. Therefore, this scenario does not consider the context-specific conceptual process design as proposed in this thesis, but it does consider a process design that is similar to the design take-off as shown in Figure 4.1. With this, the three initial choices that are mentioned in section 6.6 about the amount of PWS, bio-ethanol and bio-pellets produced are omitted.

The amount of bagasse obtained from processing the sugarcane is equal to 450,000 tb (= 60 tc/ha * 30,000 ha * 0.25 tb/tc). However, to cover the energy demand for the production of raw sugar 540,000 tb is required (= 54,000,000 kWh / 100 kWh/tb). This means that not all the energy required to process the sugarcane into raw sugar can be generated from the bagasse and thus some energy should be generated from fossil fuels. In the case that the production of raw sugar is equal to the domestic demand, the energy required in the production of raw sugar is equal to 22,500,000 kWh (= 60,000 ts / 0.08 ts/tc * 30 kWh/tc). For this, about 225,000 tb is required (= 22,500,000 kWh / 100 kWh/tb), which is more than the 187,500 tb obtained from processing the sugarcane (= 60,000 ts / 0.08 ts/tc * 0.25 tb/tc). Thus, for both processing all the sugarcane available in this scenario and for processing only the amount of sugarcane required to produce the domestic demand of 60,000 ts, the energy required for processing the sugarcane cannot be covered by the energy generation from bagasse, resulting in the fact that other energy sources are necessary. Therefore, the initial choice about the coverage of the energy demand for processing as described in section 6.6 is omitted.

8.2.2. Implications

The amount of raw sugar produced in this "status-quo" scenario is equal to 144,000 ts (= 60 tc/ha * 30,000 ha * 0.08 ts/tc), which is 84,000 ts more than the required domestic demand of 60,000 ts. This surplus of raw sugar has to be sold, otherwise the market price will collapse as the supply exceeds the demand. However, due to the declining raw sugar export market, not all the raw sugar produced in Jamaica can be sold. Consequently, the sales revenues of (some of) the factories decrease, while the production costs are already made. This scenario will inevitably involve the bankruptcy of some of the sugar factories in the near future. This also means that (some of) the farmers no longer have the possibility to deliver their sugarcane and that they therefore no longer have any income. It is not that easy for the farmers to switch to other crops in this situation, as sugarcane has a seven years grow cycle, where planting requires a high investment as described in section 2.5.

Concluding, in this "status-quo" scenario, where the process constants, process variables and the production demand are based on the current status of the Jamaican sugar industry, it is expected that the production of raw sugar will reduce to the domestic demand in the near future, which will result in the bankruptcy of some of the sugar factories and in farmers without any income but with a land filled with unusable sugarcane. Moreover, the self-sufficient sustainable bio-based economy is miles and miles away in this scenario as the amount of sugarcane available is not used to its potential and highly probably fossil fuels will be imported to satisfy the energy demand for the sugar processing.

8.3. Second Scenario - Technical Ideal

8.3.1. Design Choices

This scenario does consider the context-specific conceptual process design as proposed in this thesis, see Figure 4.5. Table 8.2 shows the process constants, process variables and production demand of the process design for a scenario based on a technical ideal situation in the Jamaican sugar industry 2018. The amount of sugarcane land is based on the harvest season 2016/2017 in the Jamaican sugar industry, see Table 5.2. An increase in sugarcane land is not considered in this scenario as it is possible to achieve the production demand by optimizing the industrial process variables. In addition, it is believed that enhancing the amount of sugarcane land is irrational as the sugar industry is diminishing and because of the opportunities of other biomass crops which can be grown on the currently unused but potential land. The bagasse yield, bio-pellet yield and the energy demand for the production of PWS, bio-ethanol and bio-pellets considered in this "technical-ideal" scenario, are based on data obtained from literature, see Table 6.1.

In this "technical-ideal" scenario, the four initial choices as mentioned in section 6.6 are defined as such that the domestic demand is achieved, that as much energy as possible is covered by the energy generation from bagasse, and that as much bio-pellets as possible are produced. Therefore, the production demand of PWS is set equal to 130,000 ts, which is in accordance with the consumption of raw sugar and refined sugar in Jamaica, see Table 5.2. The production demand of bio-ethanol is set equal to 71 million liters, which is also in accordance with the domestic consumption, see Table 5.2. The amount of energy that can be covered and the amount of bio-pellets that can be produced are dependent on the process variables, which in turn, depend on the amount of PWS and bio-ethanol produced.

One way of defining the process variables is by setting the industrial yields as high as possible, which will give a minimum required sugarcane yield. This results in a PWS yield of 0.12 ts/tc, a bio-ethanol yield of 85 l/tc and a sugarcane yield of 65 tc/ha, see Table 6.2. A bio-ethanol yield of 90 l/tc is not necessary as with this yield 78 million liters of bio-ethanol is produced, which is more than the required demand, see Appendix C. However, the amount of bagasse obtained is dependent on the amount of sugarcane processed. Thus, a higher sugarcane yield will result in more bagasse, which subsequently can be used in the energy generation and bio-pellets production. With a sugarcane yield of 65 tc/ha, a maximum of 60,000 tp can be produced assuming an energy yield of 400 kWh/tb, while with a sugarcane yield of 75 tc/ha a maximum of 102,000 tp can be produced assuming an energy yield of 600 kWh/tb, see Appendix D. Therefore, a sugarcane yield of 75 tc/ha and a energy yield of 600 kWh/tb are considered in this scenario as with those yields the bio-pellets production is as high as possible. The increase in the sugarcane yield and the energy yield are not considered as a problem in this "technical-ideal" scenario, as in this scenario the most optimal yield is chosen that is technically feasible irrespective of this is feasible in the context. With a sugarcane yield set equal to 75 tc/ha, the required PWS and bio-ethanol to satisfy the production demand are 0.10 ts/tc and 75 l/tc, respectively, see Table 6.2.

Table 8.2: The process constants, process variables and production demand for a scenario based on a technical ideal situation in the Jamaican sugar industry 2018.

		Unit
Process constants		
Sugarcane land	30,000	ha
Bagasse yield	0.25	tb/tc
Bio-pellet yield	0.5	tp/tb
Energy demand for processing		
• PWS and bio-ethanol	30	kWh/tc
• Bio-pellets	740	kWh/tb
Process variables		
Sugarcane yield	75	tc/ha
Plantation white sugar yield	0.10	ts/tc
Anhydrous bio-ethanol yield	75	l/tc
Energy yield	600	kWh/tb
Production demand		
Plantation white sugar	130,000	ts
Anhydrous bio-ethanol	71,000,000	l
Bio-pellets	100,000	tp
Energy	215,500,000	kWh

The energy demand required in the production of 130,000 ts and 71,000,000 l bio-ethanol is equal to 67,600,000 kWh (= 75 tc/ha * 30,000 ha * 30 kWh/tc). The energy demand required in the production of 100,000 t bio-pellets is equal to 148,000,000 (= 100,000 tp / 0.5 tp/tb * 740 kWh/tb). Thus, the total energy demand equals 215,500,000 kWh. Taking into account an energy yield of 600 kWh/tb, the amount of bagasse required for this amount of energy equals 359,167 tb. The total amount of bagasse obtained from the sugarcane processing is equal to 562,500 tb (= 30,000 ha * 75 tc/ha * 0.25 tb/tc), which results in the fact that there are 203,333 tb available for the bio-pellet production. Taking into account a bio-pellet yield of 0.5 tp/tb, the amount of bio-pellets that can be produced, while all the energy required for the production of PWS, bio-ethanol and bio-pellets is covered with energy generation from bagasse, equals indeed about 100,000 tp.

8.3.2. Implications

In this "technical-ideal" scenario, the self-sufficient sustainable bio-based economy in Jamaica gets a real boost by the domestic production of PWS and anhydrous bio-ethanol. In addition, with the choices made in this scenario, the dependency on import is reduced as the import of refined sugar is replaced by domestically produced PWS and the import of fossil fuels is reduced by the energy generation from bagasse. Moreover, the production of bio-pellets creates a new export market, which strengthens the position of the Jamaican sustainable bio-based economy on the world market.

However, there are several obstacles which can result in the failure of this "technical-ideal" scenario. For example, although the production of PWS and bio-ethanol equals the domestic demand, it is not guaranteed that the products can be sold. Currently, the Petroleum Corporation of Jamaica is the main player in the bio-ethanol market. According to the website of the Ministry of Science Energy and Technology, the Petroleum Corporation is primarily involved in the procurement of hydrous bio-ethanol, its dehydration, and the blending of the E10 transportation fuel, [139]. Also, in the financial appraisal of the production of bio-ethanol in Jamaica, it was noticed that fundings or subsidies are required to reduce the minimum selling price of bio-ethanol from 1.2 US$/l to the market price of 0.52 US$/l, see Figure 7.1. This means that if the Petroleum Corporation of Jamaica is not willing to purchase the domestically produced bio-ethanol and continues importing as they currently do and if the Government of Jamaica does not want to give any support by providing subsidies, it will be very hard to sell the domestically produced relatively expensive bio-ethanol. For the domestic production of PWS, the purchase is also not guaranteed. This is due to the fact that the production demand includes the replacement of the refined sugar consumption. As is described in section 4.3, the use of PWS in comparison to refined sugar enhances the operating cost of manufacturers. If the Sugar Manufacturing Corporation of Jamaica decides to keep importing refined sugar instead of using the domestically produced PWS, there will be an overproduction of PWS which will result in lower market prices as the supply exceeds the demand.

Another obstacle can be the relatively high farming yield suggested in this "technical-ideal" scenario. From the TIS analysis on the field work it followed that improving the farming best practices is not straightforward at all and requires a tremendous amount of time and effort, see section 3.3.2. Therefore, it will not be surprising that the suggested sugarcane yield increase of 15 tc/ha in comparison with the current yield cannot be achieved in the short time. As a result of a lower sugarcane yield, the amount of PWS, bio-ethanol and bio-pellets that can be produced will reduce significantly, see Appendix C and D.

In this "technical-ideal" scenario, the sugar industry of Jamaica is seen as one well-functioning 'thing' instead of the independent factories. This can imply that a completely new factory is built in accordance with the conceptual process design as suggested in the "technical-ideal" scenario. This factory is expected to cover the total consumption demand and to operate more efficiently in comparison with the current factories, as a result of which the current factories no longer have to be used. The transition from the decentralized factories to one centralized factory will result in major shifts in the sugar sector, which will obviously not be accepted by the current managing boards of the factories, but also not by the farmers as they have to transport their sugarcane all over the island to this one factory, which is not an easy task due to the very bad condition of the roads. In addition, this new factory requires a major investment for building a new sugar mill and providing all the utilities and infrastructure. The investment cost for the bio-ethanol fermentor and the pelleting plant will be lower in a centralized scenario compared to a decentralized scenario due to the economies of scale, see section 7.2. However, seeing the Jamaican sugar industry as one 'thing' can also imply that the current decentralized sugar factories have to work together and strive towards the same goal of obtaining the suggested processing yields and achieving the production demand. Major obstacles in this situation are the difficulties in communication, the differences in practices and yields between the factories, and the increased investment cost due to the economies of scale.

Concluding, it is expected that this "technical-ideal" scenario, where the process constants, process variables and the production demand are based on a technical ideal situation in the Jamaican sugar industry, will fail despite the good intentions of supporting the self-sufficient sustainable bio-based economy. The main reasons for this failure are the unrealistic assumptions that all the products produced in this scenario can be sold, that the farming yield can be improved significantly in a short time, and that the current sugar factories and sugar sector can be seen as one well-functioning 'thing'.

8.4. Third Scenario - Most Realistic

8.4.1. Design Choices

Table 8.3 shows the process constants, process variables and production demand of the process design for a scenario based on the most realistic option for the Jamaican sugar industry 2018 as considered in this thesis. The process design is based on the context-specific conceptual process design as proposed in this thesis, see Figure 4.5. In this scenario, the sugarcane land also equals 30,000 ha for the same reasons as was given for the "technical-ideal" scenario, see the previous section. The other process constants, including the bagasse yield, the bio-pellet yield and the energy demand for the production of PWS, bio-ethanol and bio-pellets considered in this "most-realistic" scenario are based on data obtained from literature, see Table 6.1.

Table 8.3: The process constants, process variables and production demand for a scenario based on the most realistic option for the Jamaican sugar industry 2018.

		Unit
Process constants		
Sugarcane land	30,000	ha
Bagasse yield	0.25	tb/tc
Bio-pellet yield	0.5	tp/tb
Energy demand for processing		
• PWS and bio-ethanol	30	kWh/tc
• Bio-pellets	740	kWh/tb
Process variables		
Sugarcane yield	60	tc/ha
Plantation white sugar yield	0.09	ts/tc
Anhydrous bio-ethanol yield	75	l/tc
Energy yield	600	kWh/tb
Production demand		
Plantation white sugar	100,000	ts
Anhydrous bio-ethanol	52,000,000	l
Bio-pellets	80,600	tp
Energy	173,288,000	kWh

The process variables and the production demand are dependent on each other, on the initial choices made, and on the feasibility of the suggested values in the context. The first two initial choices, about the amount of PWS and bio-ethanol domestically produced as mentioned in section 6.6, are highly dependent on the sugarcane yield and the possibility to sell the products on the market. In the short term, it is unrealistic to believe that the sugarcane yield can be higher than the sugarcane yield currently achieved, because improving the farming practices will require a lot of time and effort as described in section 3.3.2. Therefore, in this "most-realistic" scenario, a sugarcane yield of 60 tc/ha is considered which is equal to the current sugarcane yield, see Table 8.1. This does not mean that the improvements in the farming practices do not need to be made, but that in the short term there cannot be relied on the fact that the sugarcane yield is actually increased.

The influence of the established markets in bio-ethanol and refined sugar on the possibility to sell the domestically produced PWS and bio-ethanol is already discussed in the "technical-ideal" scenario and in section 6.5. To avoid a major overproduction of domestically produced PWS and bio-ethanol in the case those cannot be sold, it chosen to produce less PWS and bio-ethanol than domestically consumed and to combine the domestic production with the import in the established markets. With this decision, the conceptual design is integrated in the context, while it also supports the self-sufficient sustainable bio-based economy by starting to produce those products. In addition, it is expected that by cooperating with the established market instead of trying to take over them, the transition gets more supported and the possibility to completely produce the consumption demand domestically stays an option in the future.

Thus, in this scenario, there is decided upon a sugarcane yield of 60 tc/ha and a reduced production of PWS and bio-ethanol compared to the consumption demand in Jamaica. How much the production of PWS and bio-ethanol is reduced in comparison to the consumption demand is based on the most optimal combination of the processing yields. Table 8.4 shows the optimal combination of yields in relation to a reduction in the domestic production of PWS and bio-ethanol. If a trade-off was made between a higher bio-ethanol yield or a higher PWS yield it was chosen to set the PWS yield as low as possible. This is considered as most realistic, due to the fact that the bio-ethanol plant has to be installed still and the equipment can be chosen based on a specific yield. Obtaining a specific bio-ethanol yield, if not too high, is expected to be easier than improving the sugar yield in the currently installed processes. The 25%

reduction in the domestic production is chosen over the 10% and 20% reduction, because in this situation the required industrial processing yields are lower and therefore more feasible to achieve. For example, in a 25% reduction situation, the sugar yield has just to be increased from the current obtained yield of 0.08 ts/tc to only 0.09 ts/tc, see Table 8.4. Table 8.4 also shows that for a 30% reduction of the production compared to the consumption demand, the required sugarcane yield and PWS yield are equal to the current yields see Table 8.1. Therefore, a 30% reduction or more is not considered as it will not require any improvements in the current Jamaican sugar industry and thus will not give any support to establish the self-sufficient sustainable bio-based economy. Thus, the amount of PWS and bio-ethanol domestically produced in this "most-realistic" scenario are set equal to 75% of the total consumption in Jamaica, which means that the amount of PWS produced equals about 100,000 ts and the amount of bio-ethanol produced equals about 52,000,000 l. The optimal combination of yields in this "most-realistic" scenario considers the fixed sugarcane yield of 60 tc/ha, a PWS yield of 0.09 ts/tc and a bio-ethanol yield of 75 l/tc, see Table 8.4.

Table 8.4: The optimal combination of the process yields required for a reduction in the amount of PWS and bio-ethanol domestically produced in comparison to the consumption demand in Jamaica. The calculations are based on eq. (6.1), where the sugarcane land equals 30,000 ha and where the domestic consumption of sugar and bio-ethanol are 130,000 ts and 71,000,000 l, respectively. *A minimum sugarcane yield of 65 tc/ha is required to be able to produce the consumption demand.

	Reduction in domestic production					
	0%*	**10%**	**20%**	**25%**	**30%**	**40%**
Sugarcane yield	65	60	60	60	60	60
PWS yield	0.12	0.11	0.10	0.09	0.08	0.07
Bio-ethanol yield	90	85	80	75	75	65

The other two initial choices, about the amount of energy covered by the energy generation from bagasse and the amount of bio-pellets produced as mentioned in section 6.6, are mainly dependent on the energy yield and on the market prices of electricity and bio-pellets. The bagasse used for bio-pellets has a value of 30-40 US$/tb based on the market price for bio-pellets of 60-80 US$/tp as given in Table 7.1 and a bio-pellet yield of 0.5 tp/tb, see Table 8.3. The bagasse used for energy generation has a value of 80-240 US$/tb based on the market price for electricity of 0.40 US$/tp as given in Table 5.1 and an energy yield of 200-600 kWh/tb, see Table 6.1. The energy yield of 100 kWh/tb is not considered as with this energy yield not enough energy can be generated from the bagasse to cover the energy demand required in the sugarcane processing, see section 6.5.2. The fact that bagasse used in energy generation has a higher value compared to bagasse used in bio-pellets implies that the energy required during processing has to be totally covered with energy generated from bagasse, before the bagasse is used in the production of bio-pellets. In addition, the energy generation out of bagasse is expected to support the establishment of the self-sufficient sustainable bio-based economy in Jamaica as a local renewable resource is used to generate energy instead of imported fossil fuel as was also described for design choice 3.

The production of bio-pellets from bagasse is also expected to support the self-sufficient sustainable bio-based economy in Jamaica as was also described for design choice 4. In addition, there is taken advantage of the opportunities in new export markets and a foundation is laid for using other biomass crops to produce bio-pellet from in the future, see section 4.5. Therefore, the amount of bio-pellets produced is desired to be as high as possible in this scenario. Table 8.5 shows the amount of bio-pellets that can be produced taking into account different energy yields and a sugarcane yield of 60 tc/ha. In section 5.3.3, it is described that the current installed low-pressure boilers have efficiencies less than 10% resulting in a maximum energy yield of about 200 kWh/tb, while with the high-pressure/high-temperature boilers efficiencies up to 25% can be achieved resulting in energy yields up to 600 kWh/tb. To produce as much bio-pellets as possible, new boilers that can achieve high efficiencies have to be installed. If those new boilers are installed the equipment can be chosen based on the yield requirements, therefore, the relatively high energy yield of 600 kWh/tb is considered in this scenario. With the energy yield of 600 kWht/b a production of about 80,600 tonnes of bio-pellets can be achieved and the total energy demand results in about 173,288,000 kWh (= 30,000 ha * 60 tc/ha * 30 kWh/tc + 80,600 tp / 0.5 tp/tb * 740 kWh/tb).

Table 8.5: The amount of bio-pellets produced at a certain energy yield. The calculations are based on Equations (6.2) to (6.6), where the amount of sugarcane land, the bio-pellet yield, the bagasse yield, the sugarcane yield and the energy demand for processing are as given in Table 8.3. It is assumed that the production of bio-pellets can start if the energy demand for processing is satisfied by the energy generation from bagasse.

	Energy yield (kWh/tb)					
	100	**200**	**300**	**400**	**500**	**600**
Bio-pellets (tp)	0	19,149	38,942	55,236	68,951	80,597

8.4.2. Implications

In this "most-realistic" scenario the amount of production of PWS and bio-ethanol is chosen not to be equal to the consumption demand, but just a little less. With this, the risk of not being able to sell the products on the market is significantly reduced compared to what was proposed in the "technical-ideal" scenario. In addition, due to the lower production demand relatively low PWS and bio-ethanol yields are required and the sugarcane yield may even remain the same as in the current situation, see Table 8.3. However, the risk of not being able to sell the products is still there and therefore special attention has to be given to align the companies which are currently in charge of trading sugar and bio-ethanol with the plans in this scenario.

Another major obstacle is the investment needed for the installation of a fermentation, a co-generation and a bio-pellet plant. In Figure 7.1, it is shown that a bio-ethanol plant with a capacity of 71 million liters and a time period of 20 years will not generate any profit if the market price of bio-ethanol equals 0.52 US$/l. Therefore, to make the production of bio-ethanol in Jamaica financially viable, subsidies are required to reduce the minimum selling price in addition to the large investments required to install the bio-ethanol fermentors. Section 7.3 also shows that with a bio-pellet plant with a capacity of 100,000 tp and a time period of 20 years profit can be generated if the market price of bio-pellets equals 70 US$/tp. However, if the bio-pellet production is decentralized across the existing factories, a profit can only be generated if the market price of bio-pellets is higher than 80 US$/tp, see Figure 7.3. The decentralized production of PWS, bio-ethanol and bio-pellets, and also the decentralized energy generation from bagasse, will increase both the capital and operational expenses as a result of the economy of scale.

However, it is not considered realistic to replace the existing factories with one factory as was proposed as an option in the "technical-ideal" situation due to the fact that this option is ignoring the current system and that logistic problems as a result of the insufficient communication and badly maintained roads will not be surprising. Therefore, it is suggested to integrate a bio-ethanol fermentor into only three of the five existent sugar factories. Those factories should together produce the production demand of bio-ethanol and can produce PWS from the sugarcane they do not need for the bio-ethanol production. The other factories have to make sure that the production demand of PWS is achieved. With this, the investment costs are reduced. The production of bio-pellets is suggested to be completely decentralized as the logistic challenges of transporting bagasse that is susceptible to spontaneous combustion and dust explosions is not considered feasible in the current Jamaican sugar industry. The relatively high energy yield of 600 kWh/tb can also be problematic in this scenario. Besides the major investment required to install the high-pressure/high-temperature boilers, the equipment has to be properly operated and maintained, which cannot be taken for granted in the current low-tech and not so efficient sugar industry.

Concluding, in this "most-realistic" scenario, where the process constants, process variables and the production demand are based on the most realistic option for the Jamaican sugar industry as considered in this thesis, the self-sufficient sustainable bio-based economy in Jamaica is supported by producing both plantation white sugar, anhydrous bio-ethanol and bio-pellets domestically, while the energy demand required for the processes is covered by the energy generation from bagasse. In addition, with the production of bio-pellets from bagasse the first steps are taken in the trade of biomass, which can be built upon in the future. To avoid the failure of this scenario, special attention has to be given to several obstacles, among which the inclusion of the current established markets who are in charge of trading sugar and bio-ethanol, the financial viability of the processes which requires the support of investors, the government of Jamaica and other involved parties, and the steadiness of the Jamaican sugar sector regarding communication, efficiency and cooperation.

8.5. Comparison of Scenarios

In Table 8.6, the three defined scenarios are summarized in relation to the design choices. For both the "status-quo" and "technical-ideal" scenario, several negative consequences are expected, see Table 8.6. This implies that those scenarios will fail in reviving the Jamaican sugar industry and supporting the establishment of the self-sufficient sustainable bio-based economy. For the "most-realistic" scenario, also some negative consequences have to be faced and significant effort is required to make this scenario a success, but still, this scenario is proposed as feasible and realistic in the current Jamaican sugar industry.

Table 8.6: Summary of the three scenarios in relation to the design choices. (+) positive consequence, (-) negative consequence, (+/-) positive consequence for which significant effort is required.

	"Status-quo" scenario	**"Technical-ideal" scenario**	**"Most-realistic" scenario**
Design Choice 1 *Sugarcane as feedstock*	Satisfied	Satisfied (+) Options for other biomass crops	Satisfied (+) Options for other biomass crops
Design Choice 2 *PWS and bio-ethanol*	x (-) No diversification	Domestic production = domestic consumption (-) No market guarantee (-) High dependence on established markets (-) High sugarcane yield required	Domestic production <domestic consumption (+/-) Reduced market guarantee (+/-) Cooperation with established market (+) Low sugarcane yield required
Design Choice 3 *Bagasse to energy*	Partly satisfied (+) 80% energy coverage (-) Import of energy, probably based on fossil fuels	Satisfied (+) 100% energy coverage (-) High energy yield required	Satisfied (+) 100% energy coverage (-) High energy yield required
Design Choice 4 *Bio-pellets*	x (-) No diversification	100,000 tp (+) New export market created (+/-) Centralized production requires minimum selling price of 60 US$/tp	80,600 tp (+) New export market created (+/-) Decentralized production requires minimum selling price of 80 US$/tp
Design Choice 5 *Enough is enough*	x	Limited (+/-) Options for biomass gasification, bio-chemicals, etc.	Satisfied
Extra notes	(-) No market for raw sugar (-) Bankruptcy of sugar factories (-) Sugarcane farmers without income	(+) Support self-sufficient sustainable bio-based economy (-) High investments and subsidies required (-) Centralized production ignores the current situation	(+) Support self-sufficient sustainable bio-based economy (-) High investments and subsidies required (+) Decentralized production adapts to the current situation

9 Conclusion

The aim to revitalize the Jamaican sugar industry and establish a self-sufficient sustainable bio-based economy was realized by developing a context-specific conceptual process design based on diversification and integration. For this, the interface between the development of a conceptual process design itself and the feasibility of the implementation in the Jamaican sugar sector was studied. It was found that if the proposed conceptual process design was worked out for a "technical-ideal" scenario the outcomes where significantly different compared to the outcomes for the "most-realistic" scenario, which is due to the major influence of the context on the feasibility of the design. The "most-realistic" scenario is suggested to be able to revive the Jamaican sugar industry and to support the establishment of the self-sufficient sustainable bio-based economy. However, for this significant support of the Government of Jamaica is required to align the various actors related to the Jamaican sugar sector with the plans proposed in this scenario. In addition, the Government of Jamaica has to provide the financial resources required to be able to sell the produced products at globally competitive prices.

The fact that the complexity of the development of a technical process increases when it is dependent on the social system is believed not to be typical for the Jamaican sugar industry. Moreover, it is believed that the chance of success of such projects can be tremendously increased by knowledge development in this interdisciplinary field. Therefore, it is advised to study the influence of the context on the feasibility of a technology during both development, implementation and operation in all projects that consider technological transitions and/or innovations. Investors are advised to invest in projects which include this context-specific approach and to emphasize the importance of studying the influence of the context on a technology in all the projects they are involved as this will increase the chance of success of the projects. Performing a detailed study on the influence of the context on a technology is especially important when the technology is developed in or if the investment is coming from another country than where the technology is going to be executed as in this situation the context can be easily wrongly interpreted, which will inevitably result in unforeseen problems and even may lead to the failure of the project.

After performing this study, it can be concluded that there are significant opportunities to establish a self-sufficient sustainable bio-based economy in Jamaica, which is a biomass rich developing country, if besides the technical feasibility and financial viability, the proposed technologies are also suitable in the context.

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A

Photo Album

This appendix contains photos of the visits to Worthy Park Sugar Estate [meeting 4, Table 3.1] and Monymusk Sugar Estate [meeting 9, Table 3.1] during the field trip to Jamaica. In addition, some background information about the sugar estates is given. *The photos cannot be shared without permission of the author.*

Worthy Park Sugar Estate 2018-02-15

Since 1720, the production of sugarcane and sugar at Worthy Park Sugar Estate is unabated [140]. The estate has been under ownership by three families of which the Clarke family is the current owner since 1918. Approximately 210,000 tonnes of cane is milled annually of which 90,000 tonnes are supplied from the sugarcane land owned by the estate. The average annual sugar output of the factory is 24,000 tonnes, resulting in a sugar yield of 0.11 ts/tc. This sugar yield is quite high compared to the average sugar yield in Jamaica of 0.08 ts/tc, see section 2.5. This relatively high sugar yield explains the fact that the sugar factory has the highest rate on the island for efficiency every year since 1968 [140]. Worth Park Sugar Estate is also one of the factories that uses bagasse to generate energy.

Figure A.1: View over Worthy Park Sugar Estate.

Figure A.2: Sugarcane land.

Figure A.3: Sugarcane harvesting.

Figure A.4: Sugar content analysis and sugarcane storage.

Figure A.5: Sugarcane unloading, storage and feed-in to factory.

Figure A.6: Sugarcane juice extraction by dilution with water followed by pressing and an evaporation tank.

Figure A.7: Bagasse, molasses, and sugar crystals from a crystallisation tank.

Figure A.8: Cooling of cooling water

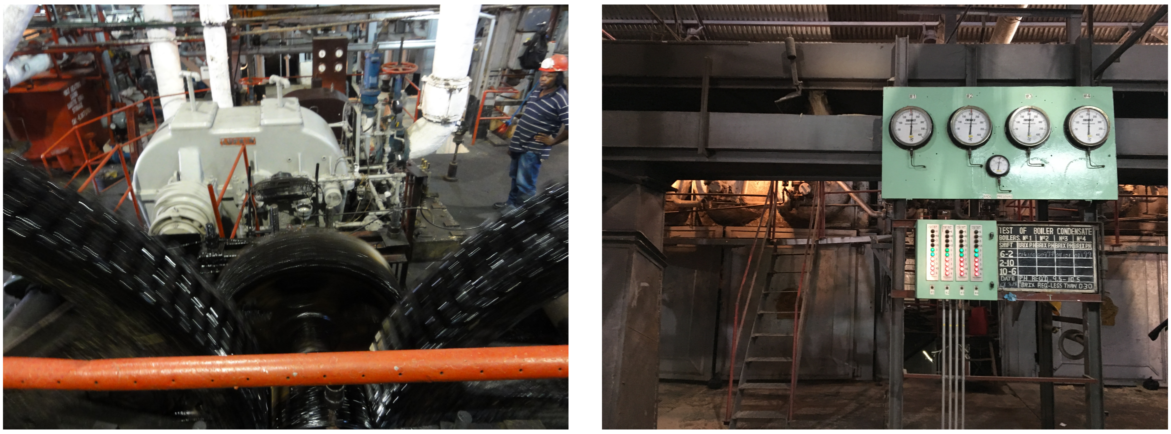

Figure A.9: Generators driving the presses and pressure controllers.

Figure A.10: View on the mountains from the factory and cleaning message.

Figure A.11: Raw sugar and sewing of bags.

Figure A.12: Storage of bags and message to all sugar lovers.

Monymusk Sugar Estate 2018-02-21

In 2009, the two largest sugar estates Monymusk and Frome, which were owned by the government, were acquired by a Chinese company in line with the privatisation strategy (see section 2.5) [meeting 2, Table 3.1]. The Chinese invested more than US$260 million to renovate the factories and sugarcane fields at both estates, however the processing yields were still disappointing [141]. In 2016, the Chinese company decided to shutter operations at the Monymusk factory to be able to concentrate on the Frome Estate. This caused the unemployment of more than 800 people at the Monymusk Estate and impaired even more people which are indirect dependent on the functioning of the factory [141]. This led the Goverment of Jamaica no choice but to interfere. The Minister of Industry, Commerce, Agriculture and Fisheries, Hon. Karl Samuda explained in a press briefing in 2017 that managing the Monymusk Sugar Factory costs the Government US$250 million [141, 142]. At the time, we were driving around at the Monymusk Estate no activity was observed on the sugarcane land or at the factory.

Figure A.13: Unkempt sugarcane field prone to bushes, trees and animals overtaking.

Figure A.14: Site of Monymusk factory.

Figure A.15: Abundance of facilities currently underused and abandoned railway.

Figure A.16: Abundance of facilities currently underused.

B

Field Notes

This appendix contains an overview of phrases of the conversations and lessons learned extracted from field notes taken by Lotte Asveld, Zoë Robaey and Sara Francke during the fieldwork in Jamaica. The lessons learned and phrases of the conversations are structured according to the TIS system functions, which are described in Table 3.2. The numbers inside the parentheses relate to the meetings given in Table 3.1.

Knowledge development and diffusion

- Tremendous effort in virology and best farming practices to prevent of diseases (1)
- Hardly any applicants for ‘promising’ Agricultural Entrepreneurship master (1)
- There is a big gap between the scientific data and the impact this data will give (1,10)
- Low yield of sugarcane per hectare (2,3-5,8,10)
- “Education is quite good, but not related to farming” (2)
- Develop technology that suits the context and let them know how to work properly with the technology (3,5)
- Opportunities in ‘smart’ farming and digital control via smart phone/tablet (1,5)
- “The working combination is both giving technical training and teach them how to be an entrepreneur” (5,6)
- “Teach them how to figure it out and how to rise up, sticking to fear is counteracting” (6)
- Teach at the level of the community and show them that there is an opportunity to earn (6)
- Transfer of knowledge within community by training programs (6,7)
- “Farmers learn from experience” (5,7,10)
- “Poor communication between sugar factories and farmers” (8,9)
- “We train the farmers, but they does not transfer this knowledge to the workers on their field” (5)
- “Making of cassava flour was not globally competitive as the raw materials are 60-70% of the total cost, our focus had to change from food processing to best practices for farming” (10)
- “Improvements and changes in technologies and farmers way of working for cassava production will have an impact on other crops, due to the tendency to imitate” (10)

Entrepreneurial experimentation

- Lack of interest in agricultural sector by young people, leaving old farmers who are low in education and conservative in style behind (1,3,5,10)
- Laziness in getting up with new technologies and maintaining existing technologies (2,8,10)
- Fear of change (2,3-5,10)
- Bring mechanization in gradually, first only with those farmers that are interested (5)
- Potential in diversification; energy, heat, plantation white, fertilizers and various crops (2-5)
- “There are farmers that are willing to experiment, mostly younger ones, however a business case and working example should been shown to them” (5,10)
- Adapt technology and machinery to make it appropriate to use in Jamaican agriculture and food processing (6)
- Making flour from different fruits and vegetables, while taking care of energy generation by solar panels and looking forward to have a bio-digester to convert agricultural waste (7)
- “We went from failed attempts to produce and sell jerk seasoning and jam, to the final promising concept of making flour” (7)
- Closing of sugar factories resulting in decreasing loans for farmers and uncertainty about where to deliver their sugarcane (3,4,8,9)
- Interest of new entrants to restart and redesign the sugar factory at Monymusk (9)
- “Carrot model is based on subsidies, is this sustainable as it is definitely not economically feasible?” (10)
- “There is something in between the carrot and the stick model, called cooperation and collaboration, however this takes time and effort” (10)

Influence on the direction of search

- A lack of acceptance and legislation to get a transgenic papaya in production and on the market (1)
- “You really have to show the farmers they need to change, they won’t believe you on your research” (1,10)
- Growing awareness regarding the influence of climate change; heavy dry and wet seasons (1-8,10)
- If agriculture does not grow the economy does not grow (1,4,5)
- Positive and negative governmental interference on the sugar industry (2,4,8,9)
- Thousands of jobs have to be saved, for mostly uneducated people (2,8,9)
- With every election there are changes for farmers employed by the government (5)
- Formation of Jeffrey Town Farmers Association as reaction on collapsed preferential prices of bananas resulting in a very poor livelihood in the parish (7)
- "Hurricane Ivan destroyed major parts of the land and food became a scarcity” (7)
- “34% of Jeffrey town is unemployed, we have to make opportunities” (7)
- “We need mechanical harvesting, we need diversification and we need trust for the profit of the farmer” (5,8)
- “Making of cassava flour was not globally competitive as the raw materials are 60-70% of the total cost, our focus had to change from food processing to best practices for farming” (10)
- “We have no choice but to fight the deteriorating agricultural industry, otherwise nothing will happen” (10)

Market formation

- Fall away of preferential treatments and price agreements are main causes for crumbling sugar industry (1,2,4,10)
- "Import gives security of quantity and quality" (1)
- If agriculture does not grow the economy does not grow (1,4,5,9)
- "We have to see sugar as a by-product to keep the agricultural industry alive" (2)
- Small farms obtain more difficulties compared to medium and large sized farms (2,4,5)
- Adapt technology and machinery to make it appropriate to use in Jamaican agriculture and food processing (6)
- "We make a breakfast porridge that we sell to schools" (7)
- Uncertainty about the effects of Brexit on trading with UK and EU (8)
- "To export something is extremely difficult, while importing something is extremely simple" (10)
- "Our sugar costs more than the one we import as we have a smaller market and the absence of proper technology" (10)
- "If we cannot produce sugar competitively, how can we make bio-ethanol economically feasible?" (10)

Resource mobilization

- Lack of structure and technology (1,2,5,8-10)
- Producing refined sugar is to capital intensive as the total capacity is low (2,4)
- "If the refinery is efficient enough it could stop at the A strike, and the rest can be used as feedstock for biofuels, energy, and heat" (2)
- Money! Replant the field, provide equipment, knowledge and experience (2,3,8,9)
- They want the money, but they do not want to do anything for it. So the structure of providing them everything and just paying them for keeping an eye, seems like a more suitable example compared to educate them and give them the responsibility. It is a feeling of working for someone else, but they also have their own land, buildings, and a part of the responsibility (2)
- Right balance between giving and strictness (2,10)
- Funding from for example community based organisations, government and grants (1,6-8)
- Badly maintained roads (4,6-10)
- "We would really want mechanization, not to harvest as the soil is not appropriate for this and they need the jobs, but to be able to plant more efficiently" (7)
- "People like us cannot afford to borrow money from the bank to pay the high land fees" (7)
- EU is the largest single donor to Jamaica (8)
- "Farmers need to take care of transport instead of the factories, which make them economically weaker and subsidies are not approved yet" (8)
- The farmers need to get support to get back on their feed, a lot of land is out of sugar and they do not have the money to replant it (3,8,9)
- "The roads that are repaired are political and economic chosen, most of the repaired roads are not even used for sugar transport" (8)
- "We have to deal with aging equipment and aging farmers" (4,8,10)
- "Good extension means giving equipment, knowledge, etc. for free and emphasis responsibility for the equipment, soil and crops" (10)

Legitimation

- A lack of acceptance and legislation to get genetically modified papaya's in production and on the market (1)
- "You have to do it for them, you have to show the farmers, they won't believe you on your word" (1,2,10)
- Lack of interest in agricultural sector by young people, leaving old farmers who are low in education and conservative in style behind (1,3,5,10)
- "Speaking to the farmers is not the problem, them taking our advice is" (1)
- "Our country is not properly organized with respect to agriculture" (2)
- "Worthy Park Sugar Estate is the only really profitable one, cause they have real owners" (2,4)
- "If something goes wrong in the whole process, no one talks because everyone is related" (4)
- Lack of trust and feasibility with bamboo-to-energy, however this trust and feasibility is there in the sugar industry (2,4)
- To convince the farmers, you need the right person on the right place, preferably someone from the community (2,4,6,7)
- "It is an era of depression, the moral is very low" (3)
- "There are farmers that are willing to experiment, mostly younger ones, however a business case and working example should been shown to them" (5)
- "Understanding the background of the people you are talking to is the only way to have an open conversation, be rootsie" (6)
- It is about knowing who you are speaking to, as they won't listen and speak to you until they feel respected (6)
- "It is a community effort; building the infrastructure and organizing activities" (7)
- "The politics did not gave us the money for machines, they want us to stay poor" (7)
- "From a very young age people told me I have to leave, but I always knew I wanted to stay and fight for it" (7)
- "All what you heard in this meeting is realistic and true, however it should not be interpreted as sugar industry is dead! It is still a large business which contains lots of opportunities which should be taken now" (8)
- "You can lead a horse to water, but you cannot make it drink" (10)

C

Production of Plantation White Sugar and Anhydrous Bio-ethanol

To study the influence of the sugarcane yield, the PWS yield and the bio-ethanol yield on the amount of PWS and bio-ethanol that can be produced, the amount of bio-ethanol produced is calculated by the following equation:

$$\text{Ethanol (l)} = \text{ethanol yield (l/tc)} * (\text{sugarcane yield (tc/ha)} * \text{sugar land (ha)} - \frac{\text{PWS (ts)}}{\text{PWS yield (ts/tc)}}) \qquad \text{(C.1)}$$

where the bio-ethanol yield is varied between 65-90 l/tc, the sugarcane yield is varied between 55-80 tc/ha, the amount of sugarcane land is fixed at 30,000 ha, the amount of PWS is varied between 100,000-130,000 ts and the PWS yield is varied between 0.07-0.12 ts/tc, see Table 5.2 and Table 6.1.

The bio-ethanol production is calculated for two different amounts of PWS produced. In the first option, the PWS production equals the domestic consumption of 130,000 ts and in the second option the PWS production is reduced to about 75% of the domestic consumption, so 100,000 ts, see Table 5.2. With those two options an idea is given about the effect of the initial choice on how much PWS should be produced on the required processing yields. It is assumed that the production of bio-ethanol can start if the chosen demand of PWS is satisfied.

The red marked cells in the tables indicate that with the specific combination of yields the production of PWS is not satisfied, so no bio-ethanol can be produced. The green marked cells in the tables indicate that with the specific combination of yields both the aimed production of PWS and bio-ethanol are satisfied. The orange marked cells indicate the variables that are changed for the different cases.

Option 1: Plantation white sugar production of 130,000 ts

*Ethanol (l) = *10^6

Fixed

Sugarland	30000	ha
Anhydrous bio-ethanol yield	65	l/tc
Plantation white sugar	130000	ts

Aim

Anhydrous bio-ethanol	71000000	l

Ethanol (l)	Sugarcane yield (tc/ha) →					
↓ Pws yield (ts/tc)	55	60	65	70	75	80
0.07	0.00	0.00	6.04	15.79	25.54	35.29
0.08	1.63	11.38	21.13	30.88	40.63	50.38
0.09	13.36	23.11	32.86	42.61	52.36	62.11
0.1	22.75	32.50	42.25	52.00	61.75	71.50
0.11	30.43	40.18	49.93	59.68	69.43	79.18
0.12	36.83	46.58	56.33	66.08	75.83	85.58

Fixed

Sugarland	30000	ha
Anhydrous bio-ethanol yield	70	l/tc
Plantation white sugar	130000	ts

Aim

Anhydrous bio-ethanol	71000000	l

Ethanol (l)	Sugarcane yield (tc/ha) →					
↓ Pws yield (ts/tc)	55	60	65	70	75	80
0.07	0.00	0.00	6.50	17.00	27.50	38.00
0.08	1.75	12.25	22.75	33.25	43.75	54.25
0.09	14.39	24.89	35.39	45.89	56.39	66.89
0.1	24.50	35.00	45.50	56.00	66.50	77.00
0.11	32.77	43.27	53.77	64.27	74.77	85.27
0.12	39.67	50.17	60.67	71.17	81.67	92.17

Fixed

Sugarland	30000	ha
Anhydrous bio-ethanol yield	75	l/tc
Plantation white sugar	130000	ts

Aim

Anhydrous bio-ethanol	71000000	l

Ethanol (l)	Sugarcane yield (tc/ha) →					
↓ Pws yield (ts/tc)	55	60	65	70	75	80
0.07	0.00	0.00	6.96	18.21	29.46	40.71
0.08	1.88	13.13	24.38	35.63	46.88	58.13
0.09	15.42	26.67	37.92	49.17	60.42	71.67
0.1	26.25	37.50	48.75	60.00	71.25	82.50
0.11	35.11	46.36	57.61	68.86	80.11	91.36
0.12	42.50	53.75	65.00	76.25	87.50	98.75

(Option 1 continued)

*Ethanol (l) = *10^6

Fixed

Sugarland	30000	ha
Anhydrous bio-ethanol yield	80	l/tc
Plantation white sugar	130000	ts

Aim

Anhydrous bio-ethanol	71000000	l

Ethanol (l)	Sugarcane yield (tc/ha) → 55	60	65	70	75	80
↓ Pws yield (ts/tc) 0.07	0.00	0.00	7.43	19.43	31.43	43.43
0.08	2.00	14.00	26.00	38.00	50.00	62.00
0.09	16.44	28.44	40.44	52.44	64.44	76.44
0.1	28.00	40.00	52.00	64.00	76.00	88.00
0.11	37.45	49.45	61.45	73.45	85.45	97.45
0.12	45.33	57.33	69.33	81.33	93.33	105.33

Fixed

Sugarland	30000	ha
Anhydrous bio-ethanol yield	85	l/tc
Plantation white sugar	130000	ts

Aim

Anhydrous bio-ethanol	71000000	l

Ethanol (l)	Sugarcane yield (tc/ha) → 55	60	65	70	75	80
↓ Pws yield (ts/tc) 0.07	0.00	0.00	7.89	20.64	33.39	46.14
0.08	2.13	14.88	27.63	40.38	53.13	65.88
0.09	17.47	30.22	42.97	55.72	68.47	81.22
0.1	29.75	42.50	55.25	68.00	80.75	93.50
0.11	39.80	52.55	65.30	78.05	90.80	103.55
0.12	48.17	60.92	73.67	86.42	99.17	111.92

Fixed

Sugarland	30000	ha
Anhydrous bio-ethanol yield	90	l/tc
Plantation white sugar	130000	ts

Aim

Anhydrous bio-ethanol	71000000	l

Ethanol (l)	Sugarcane yield (tc/ha) → 55	60	65	70	75	80
↓ Pws yield (ts/tc) 0.07	0.00	0.00	8.36	21.86	35.36	48.86
0.08	2.25	15.75	29.25	42.75	56.25	69.75
0.09	18.50	32.00	45.50	59.00	72.50	86.00
0.1	31.50	45.00	58.50	72.00	85.50	99.00
0.11	42.14	55.64	69.14	82.64	96.14	109.64
0.12	51.00	64.50	78.00	91.50	105.00	118.50

Option 2: Plantation white sugar production of 100,000 ts

*Ethanol (l) = *10^6

Fixed

Sugarland	30000	ha
Anhydrous bio-ethanol yield	65	l/tc
Plantation white sugar	100000	ts

Aim

Anhydrous bio-ethanol	71000000	l

Ethanol (l)		Sugarcane yield (tc/ha) →					
		55	60	65	70	75	80
↓ Pws yield (ts/tc)	0.07	14.39	24.14	33.89	43.64	53.39	63.14
	0.08	26.00	35.75	45.50	55.25	65.00	74.75
	0.09	35.03	44.78	54.53	64.28	74.03	83.78
	0.1	42.25	52.00	61.75	71.50	81.25	91.00
	0.11	48.16	57.91	67.66	77.41	87.16	96.91
	0.12	53.08	62.83	72.58	82.33	92.08	101.83

Fixed

Sugarland	30000	ha
Anhydrous bio-ethanol yield	70	l/tc
Plantation white sugar	100000	ts

Aim

Anhydrous bio-ethanol	71000000	l

Ethanol (l)		Sugarcane yield (tc/ha) →					
		55	60	65	70	75	80
↓ Pws yield (ts/tc)	0.07	15.50	26.00	36.50	47.00	57.50	68.00
	0.08	28.00	38.50	49.00	59.50	70.00	80.50
	0.09	37.72	48.22	58.72	69.22	79.72	90.22
	0.1	45.50	56.00	66.50	77.00	87.50	98.00
	0.11	51.86	62.36	72.86	83.36	93.86	104.36
	0.12	57.17	67.67	78.17	88.67	99.17	109.67

Fixed

Sugarland	30000	ha
Anhydrous bio-ethanol yield	75	l/tc
Plantation white sugar	100000	ts

Aim

Anhydrous bio-ethanol	71000000	l

Ethanol (l)		Sugarcane yield (tc/ha) →					
		55	60	65	70	75	80
↓ Pws yield (ts/tc)	0.07	16.61	27.86	39.11	50.36	61.61	72.86
	0.08	30.00	41.25	52.50	63.75	75.00	86.25
	0.09	40.42	51.67	62.92	74.17	85.42	96.67
	0.1	48.75	60.00	71.25	82.50	93.75	105.00
	0.11	55.57	66.82	78.07	89.32	100.57	111.82
	0.12	61.25	72.50	83.75	95.00	106.25	117.50

(Option 2 continued)

*Ethanol (l) = *10^6

Fixed

Sugarland	30000	ha
Anhydrous bio-ethanol yield	80	l/tc
Plantation white sugar	100000	ts

Aim

Anhydrous bio-ethanol	71000000	l

Ethanol (l)	Sugarcane yield (tc/ha) →					
↓ Pws yield (ts/tc)	55	60	65	70	75	80
0.07	17.71	29.71	41.71	53.71	65.71	77.71
0.08	32.00	44.00	56.00	68.00	80.00	92.00
0.09	43.11	55.11	67.11	79.11	91.11	103.11
0.1	52.00	64.00	76.00	88.00	100.00	112.00
0.11	59.27	71.27	83.27	95.27	107.27	119.27
0.12	65.33	77.33	89.33	101.33	113.33	125.33

Fixed

Sugarland	30000	ha
Anhydrous bio-ethanol yield	85	l/tc
Plantation white sugar	100000	ts

Aim

Anhydrous bio-ethanol	71000000	l

Ethanol (l)	Sugarcane yield (tc/ha) →					
↓ Pws yield (ts/tc)	55	60	65	70	75	80
0.07	18.82	31.57	44.32	57.07	69.82	82.57
0.08	34.00	46.75	59.50	72.25	85.00	97.75
0.09	45.81	58.56	71.31	84.06	96.81	109.56
0.1	55.25	68.00	80.75	93.50	106.25	119.00
0.11	62.98	75.73	88.48	101.23	113.98	126.73
0.12	69.42	82.17	94.92	107.67	120.42	133.17

Fixed

Sugarland	30000	ha
Anhydrous bio-ethanol yield	90	l/tc
Plantation white sugar	100000	ts

Aim

Anhydrous bio-ethanol	71000000	l

Ethanol (l)	Sugarcane yield (tc/ha) →					
↓ Pws yield (ts/tc)	55	60	65	70	75	80
0.07	19.93	33.43	46.93	60.43	73.93	87.43
0.08	36.00	49.50	63.00	76.50	90.00	103.50
0.09	48.50	62.00	75.50	89.00	102.50	116.00
0.1	58.50	72.00	85.50	99.00	112.50	126.00
0.11	66.68	80.18	93.68	107.18	120.68	134.18
0.12	73.50	87.00	100.50	114.00	127.50	141.00

D

Energy Generation and Production of Bio-pellets from Bagasse

To study the influence of the sugarcane yield and the energy yield from bagasse on the amount of bagasse required to generate energy and the amount of bagasse available to produce bio-pellets, the amount of bio-pellets produced is calculated by the following equations:

$$\textbf{Pellets (tp)} = \text{pellet yield (tp/tb)} * (\text{bagasse (tb)} - \text{bagasse for energy (tb)}) \tag{D.1}$$

$$\text{Bagasse (tb)} = \text{bagasse yield (tb/tc)} * \text{sugarcane yield (tc/ha)} * \text{sugar land (ha)} \tag{D.2}$$

$$\text{Bagasse for energy (tb)} = \frac{\text{energy-SE (kWh)} + \text{energy-P (kWh)}}{\text{energy yield from bagasse (kWh/tb)}} \tag{D.3}$$

$$\text{Energy-SE (kWh)} = \text{energy-SE (kWh/tc)} * \text{sugarcane yield (tc/ha)} * \text{sugar land (ha)} \tag{D.4}$$

$$\text{Energy-P (kWh)} = \frac{\text{energy-P (kWh/tb)}}{\text{pellets yield (tp/tb))}} * \textbf{pellets (tp)} \tag{D.5}$$

where the bio-pellet yield is 0.5 tp/tb, the bagasse yield is 0.25 tb/tc, the sugarcane yield is varied between 55-80 tc/ha, the amount of sugarcane land is fixed at 30,000 ha, the energy yield from bagasse is varied between 100-600 kWh/tb, the energy demand for the production of plantation white sugar and anhydrous bio-ethanol (energy-SE) equals 30 kWh/tc, and the energy demand for the production of bio-pellets (energy-P) equals 740 kWh/tb, see Table 5.2 and Table 6.1.

To obtain the amount of bio-pellets that can be produced, the bagasse needed to satisfy the energy demand for processing should be known. However, to define the energy demand for pelleting, the amount of bio-pellets produced should be known. To solve this self-dependency problem, the amount of bio-pellets produced in Equation (D.5) is fixed by an initial choice. The initial choice is defined to be between 0-100,000 tonnes of bio-pellets. This range is covered by six options with steps of 20,000 tonnes of bio-pellets. For every option, the bio-pellet production taking into account the energy demand of the fixed amount of bio-pellets, is calculated by Equation (D.1).

It is assumed that the production of bio-pellets can start if the energy demand for processing is satisfied by the energy generation from bagasse. The red marked cells in the tables indicate that with the specific combination of yields there is not enough bagasse to satisfy the energy demand for processing. The green marked cells in the tables indicate that with the specific combination of the sugarcane and energy yield, both the energy demand for processing (including the energy demand of the fixed amount of bio-pellets produced) and the production of the set amount of bio-pellets can be achieved. The orange cells indicate the variables that are changed in the different cases.

Bagasse for energy generation and bio-pellets production

*Bio-pellets (tp) = *10^3

Fixed		
Sugarland	30000	ha
Bio-pellets yield	0.5	tp/tb
Bagasse yield	0.25	tb/tc
Energy for sugar and ethanol	30	kWh/tc
Energy for bio-pellets	740	kWh/tb
Produced		
Bio-pellets	0	tp

Pellets (tp)		Sugarcane yield (tc/ha) →					
		55	60	65	70	75	80
← Energy yield (kWh/tb)	100	0	0	0	0	0	0
	200	83	90	98	105	113	120
	300	124	135	146	158	169	180
	400	144	158	171	184	197	210
	500	157	171	185	200	214	228
	600	165	180	195	210	225	240

Fixed		
Sugarland	30000	ha
Bio-pellets yield	0.5	tp/tb
Bagasse yield	0.25	tb/tc
Energy for sugar and ethanol	30	kWh/tc
Energy for bio-pellets	740	kWh/tb
Produced		
Bio-pellets	20000	tp

Pellets (tp)		Sugarcane yield (tc/ha) →					
		55	60	65	70	75	80
← Energy yield (kWh/tb)	100	0	0	0	0	0	0
	200	9	16	24	31	39	46
	300	74	86	97	108	119	131
	400	107	121	134	147	160	173
	500	127	141	156	170	184	198
	600	140	155	170	185	200	215

Fixed		
Sugarland	30000	ha
Bio-pellets yield	0.5	tp/tb
Bagasse yield	0.25	tb/tc
Energy for sugar and ethanol	30	kWh/tc
Energy for bio-pellets	740	kWh/tb
Produced		
Bio-pellets	40000	tp

Pellets (tp)		Sugarcane yield (tc/ha) →					
		55	60	65	70	75	80
← Energy yield (kWh/tb)	100	0	0	0	0	0	0
	200	0	0	0	0	0	0
	300	25	36	48	59	70	81
	400	70	84	97	110	123	136
	500	98	112	126	140	155	169
	600	116	131	146	161	176	191

(continued)

*Bio-pellets (tp) = *10^3

Fixed

Sugarland	30000	ha
Bio-pellets yield	0.5	tp/tb
Bagasse yield	0.25	tb/tc
Energy for sugar and ethanol	30	kWh/tc
Energy for bio-pellets	740	kWh/tb

Produced

Bio-pellets	60000	tp

Pellets (tp)		Sugarcane yield (tc/ha) →					
		55	60	65	70	75	80
← Energy yield (kWh/tb)	100	0	0	0	0	0	0
	200	0	0	0	0	0	0
	300	0	0	0	10	21	32
	400	33	47	60	73	86	99
	500	68	82	96	111	125	139
	600	91	106	121	136	151	166

Fixed

Sugarland	30000	ha
Bio-pellets yield	0.5	tp/tb
Bagasse yield	0.25	tb/tc
Energy for sugar and ethanol	30	kWh/tc
Energy for bio-pellets	740	kWh/tb

Produced

Bio-pellets	80000	tp

Pellets (tp)		Sugarcane yield (tc/ha) →					
		55	60	65	70	75	80
← Energy yield (kWh/tb)	100	0	0	0	0	0	0
	200	0	0	0	0	0	0
	300	0	0	0	0	0	0
	400	0	10	23	36	49	62
	500	38	53	67	81	95	110
	600	66	81	96	111	126	141

Fixed

Sugarland	30000	ha
Bio-pellets yield	0.5	tp/tb
Bagasse yield	0.25	tb/tc
Energy for sugar and ethanol	30	kWh/tc
Energy for bio-pellets	740	kWh/tb

Produced

Bio-pellets	100000	tp

Pellets (tp)		Sugarcane yield (tc/ha) →					
		55	60	65	70	75	80
← Energy yield (kWh/tb)	100	0	0	0	0	0	0
	200	0	0	0	0	0	0
	300	0	0	0	0	0	0
	400	0	0	0	0	12	25
	500	9	23	37	52	66	80
	600	42	57	72	87	102	117

E

Project Charter

Project Charter

Project Manager	Sara Francke
Project Title	Development of a context-specific conceptual process design for the Jamaican sugar industry.
Specific goals	Support the self-sufficient sustainable bio-based economy in Jamaica
Timeline	Final report: mid-September
	Defence: end of September
Project Scope	
In-scope	Background information of Jamaica
	Field trip to Jamaica
	Fieldwork analysis
	Choice of biomass feedstock
	Choice of bio-based product
	Database creation
	Context-specific conceptual process design
	Block flow diagram
	Financial overview
Out-of-scope	Technology invention
	Detailed technical design (equipment, process & control details)
Deliverable	Context-specific conceptual process design
	Feasibility analysis of different scenarios

F Project Timeline

Date	Duration	Action	Extra
2018-01-22	3 weeks	Information about Jamaica Literature search biorefinery Set up questions	Prepare travel Meeting André de Haan Call Joseph Maceda Call Joop Groen (Viride) Call Anton Robek
2018-02-11	3 weeks	Fieldwork in Jamaica	Work-out minutes
2018-03-05	1 week	Holiday - jetlag	
2018-03-12	2 weeks	Reflect on questions Define project options Search for methodologies Literature search	Photo album for partners Meeting Viride Call Joseph Maceda
2018-03-23	x	Kick-off meeting	Attendees: André de Haan, Lotte Asveld, John Posada, Zoë Robaey, Eva Geschiere
2018-03-26	3 weeks	Write preface Write introduction Structure research Define research scope Make a project charter Data collection Think about methods	Visit Bioprocess Pilot Facility Plan meeting with committee Mail Joseph Maceda Mail + meeting Viride Mail David Silvera
2018-03-29	x	Presentation at BTS	
2018-04-16	3 weeks	Write introduction Write methods Fieldwork analysis Supply chain model Swot analysis Design choices	NDA with Viride LateX Mail David Silvera
2018-05-04	x	Meeting with Committee	Attendees: André de Haan, Lotte Asveld, Zoë Robaey
2018-05-07	3 weeks	Research question Rewrite introduction Specify fieldwork analysis Data collection Specify design choices	NDA with Viride Call David Silvera Mail Michiel Makkee Meeting Rafael Silva Capaz LateX

Date	Duration	Action	Extra
2018-05-28	3 weeks	Data collection Model scenarios Sensitivity analysis Check consistency of report	Meeting Mar Palmeros Parada Mail David Silvera Mail Allan Rickards Mail Viride Plan meeting with committee Plan defence date
2018-06-18	1 week	Holiday	
2018-06-25	2 weeks	Data collection Literature on pellets Photo album in appendix Block flow diagram	Prepare presentation IBIS Mail Allan Rickards Mail David Silvera and Philip Henriques Meeting Lorena Paz Saavedra Ask feedback Zoë Robaey
2018-06-28	x	Presentation at IBIS progress meeting	
2018-07-09	3 weeks	Data collection Chapter Fieldwork Chapter Design Choices Chapter Database Block flow diagram Feedback Zoë Robaey	Prepare meeting committee Mail Hans van der Sluis Mail Anton Robek Meeting Andreia Camargo Marques Postal Ask feedback Lotte Asveld
2018-07-10	x	Meeting with Committee	Attendees: André de Haan, Lotte Asveld
2018-07-30	2 weeks	Chapter Database Block flow diagram Feedback Lotte Asveld	
2018-08-13	2 weeks	Holiday	
2018-08-27	2 weeks	Chapter Database Block flow diagram Preface Nomenclature Financial overview Discussion Introduction	Mail Joe Maceda Mail Rafael Silva Capaz Meeting Lorena Paz Saavedra Feedback Zoë Robaey
2018-09-12	x	Draft version	Recipients: André de Haan, Lotte Asveld, Zoë Robaey
2018-09-13	1 week	Feedback Conclusion Abstract Bibliography Appendices	
2018-09-21	x	Final version	Recipients: André de Haan, Lotte Asveld, Michiel Makee, Zoë Robaey
2018-09-22	weekend	Prepare presentation Prepare defense	
2018-09-25	x	Defense	