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**Cassava Bio Refinery - A Mass and Energy  
Balance**  
**Bio Refinaria de Mandioca - Um Balanço de  
Massa e Energia**

CAMPINAS  
2018

**Caryl Andre Barquero Schutze**

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Balance  
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do título de Mestre em Engenharia Mecânica, na  
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ORIENTADOR: Prof. Dr. Waldir Antônio Bizzo

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## **Dedication**

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*There is perhaps no better demonstration of the folly of human conceits than this distant image of our tiny world. To me, it underscores our responsibility to deal more kindly with one another, and to preserve and cherish the pale blue dot, the only home we've ever known.*

---

Carl Sagan

## **Abstract**

This dissertation is an evaluation of the technical requirements of mass, energy and equipment in order to create a mixed cassava mill that produces both ethanol and starch from the cassava root much like a modern sugar cane mill produces both ethanol and sugar. In order to properly create a parallel between modern Brazilian sugar cane mills and the proposed cassava mill, a complete characterization of the cassava plant residue as possible solid fuel source for the industrial process was made. Also, as the mill would be considered a complete and mid scale biorefinery, an estimate was calculated for the probable electric energy by-product that would in turn be sold to the national market.

*Key-words:* Cassava, Ethanol, Starch, Renewable Energy.

## Resumo

Esta dissertação é uma avaliação dos requisitos técnicos de massa, energia e equipamentos para criar uma usina mista de mandioca que produz tanto etanol quanto amido da raiz de mandioca, como uma moderna usina de cana-de-açúcar. produz etanol e açúcar. A fim de criar adequadamente um paralelo entre as modernas usinas de cana-de-açúcar brasileiras e proposta da fábrica de mandioca, uma caracterização completa do resíduo da planta da mandioca como possível fonte de processo industrial foi feito. Além disso, como a usina seria considerada uma biorrefinaria de escala completa e média, uma estimativa foi calculada para o provável subproduto da energia elétrica que, por sua vez, seria vendido ao mercado nacional.

*Palavras-chave:* Mandioca, Etanol, Amido, Energia Renovável.



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# 1 Introduction

Energy, a source of wealth in its abundance and a heavy economic burden in its absence, represents one of the corner stones of our modern world. The ever expanding need for reliable fuel sources as more and more human beings rise out of subsistence living is one that comes in conflict with our planets diminishing tolerance to our CO<sub>2</sub> emissions. With this in mind, the search for new renewable energy sources has become the beacon of any modern economy. Agriculture and its residues are again seen with "energetic" eyes as the world looks to biomass as a palliative medicine to an over heated Earth. Biomass, that incinerated, gasified or liquefied, can help to generate enough energy to feed the world's growing economies, fuel cars, light our cities and keep the gears of industry churning.

In this search, Brazil has become a world leader in the use of bioethanol derived from the sugar cane plant. Yet it is with an interest in expanding the possible sources of biofuels to enable new energetic matrices other than sugar cane that this dissertation came to be. As the world transitions from fossil fuels to "greener" fuels, a plethora of sources are necessary in order to prevent the already perceived environmental pitfall of mono-cropping. So in the spirit of problem-solving, one is forced to look for solutions perhaps already discovered, looked over or just plainly not studied in depth.

In any sense, the main agricultural crops of most tropical regions provide an extensive list of possible biomasses that can be properly, or at the least, technically transformed into massive fuel sources. Brazil, with its massive size, spanning various latitudes, is again, one of the most diverse regions for agricultural production in the world. Here, from one of the most common food staples, the cassava root has already been established as a possible source of mass produced bioethanol by various other academic works and empirical enterprises. However, utilizing food-stuff as an energy vector carries some social and economic costs. These costs, multiplied by the fact that the cassava root is an important source of calories for millions of people throughout the world, requires various innovations in any an all chains of the production of cassava, wheter they be agricultural, logistical or industrial in order to maintain the balance between food and fuel source.

## 1.1 Industrial cassava ethanol in Brazil: its "roots"

Although the cassava root was already used for centuries for the production of beers by the native population of Brazil and other countries of Latin America, the first industrial cassava ethanol mill was only officially opened in the year 1932. The Gravatá Ethanol Mill (Fig. 1.1) located in the city of Divinópolis, Minas Gerais was the first carburant ethanol production facility in Latin America. It functioned as such until the late 1940's, early 1950's until it shifted

productions to cassava flour and other cassava food-stuffs.



Figure 1.1: The Gravatá Mill in Divinópolis  
SOURCE: (DIVINÓPOLIS, 2017).

Later attempts to produce large-scale cassava ethanol facilities in Brazil came with the creation of the National Alcohol Program or *Pró-Álcool* in Portuguese. The program began the 14th of November, 1975, created by Federal Decree n° 76.593 (CASTRO; SCHWARTZMAN, 2008). Although this program is mostly known for its successes in sugar cane ethanol production, the incessant search for fuel independence by the Brazilian Federal Government targeted cassava ethanol production as a major possible input for the ever growing demand for biofuel. The effort was able to secure some investments for the research and development of many of the technologies necessary not only to augment the agricultural output of the cassava fields, but to increase the industrial efficiencies of the starch conversions, fermentation and later distillation.

The National Institute of Technology, or INT for its initials in Portuguese, led these developments as well as other Brazilian research centers. Already in 1977, two years after the initial creation of the program, an ethanol distillery was already built in a partnership between the Brazilian petroleum company, Petrobras, and the INT (CASTRO; SCHWARTZMAN, 2008). Petrobras, as a public owned enterprise, was incredibly interested in the production of ethanol from cassava based sources as it would not have to deal with the already vested interests of sugar-cane plantations in the State of São Paulo and the Northeast region. Petrobras executives required of the engineers at INT that this new distillery that would be located in the city of Curvelo, Minas Gerais, to produce 300,000 litres per day of ethanol, something that the INT

staff considered as imprudent, due to the lack of technical understanding of the entire industrial process. At the end, the Curvelo Distillery produced 60,000 litres per day with ethanol yields of approximately 145 litres per ton of root, until it closed two years later due to problems with unreliable agricultural inputs. The mill used discontinuous batch hydrolysis process with enzymatic saccharification which at the time meant in importing enzymes from Europe or the United States, increasing the cost of the process (LIMA, 2007).

The *Pró-Álcool* program created 8 more cassava ethanol projects, however, they all failed due to the lack of stability in the availability of roots, both due to agricultural issues and to rises in root costs. One must note, that most of these projects were located in areas that were not really suitable for the production of cassava roots. Curvelo in Minas Gerais, Sinop in the state of Mato Grosso do Sul, and other regions that at one point where cassava production was once very strong were the sites chosen for the blooming cassava ethanol industry (ESTADO, AGENCIA, 2006). Yet the only distillery that remains open since the *Pró-Álcool* era is the Coraci Distillery, located in São Pedro do Turvo, São Paulo (GAZETA, 2006). However due to higher market prices, it does not generate electricity produces neutral ethanol for pharmaceutical use.

## 1.2 The "flex" mill

As it was stated before, the particular status of the cassava plantations in present day Brazil renders a problem of major economic opportunity costs in order to properly exploit cassava ethanol as a carburant fuel source. A "flex" mill that produces both ethanol and/or starch from cassava roots can provide a reduction of some of the opportunity costs of turning an important food staple for the Brazilian people and millions of other across the globe into fuel. Just as sugar cane mills exploit their ability to convert within certain boundaries their production from ethanol to sugar as prices for their products fluctuate, the cassava mill can follow the same concept, lowering some of the cost of having an either pure ethanol production or pure starch. By inserting this degree of manoeuvrability into production, an economic incentive is put in place so as to implement the necessary equipment for the production of cassava ethanol.

## 1.3 Use of the cassava residue for energy generation

Usually, agricultural field residues are of no use in the industrial processing of its main crop. Mainly it is left on the field to protect the field from wind and water erosion. It also plays a not insignificant role in the nutrient recuperation of the field as it decomposes and deposits its material back on the ground. However, more and more is the possibility of using those same residues to generate both thermal and electricity enticing researcher and engineers. "The times

are a' changing" as a poet once said and when discarded biomass was once only considered as field residue it is now being considered a major possible energy source for the future of humanity.

The use of the cassava field residues were already studied and its potentials for bioenergy generation gathered by numerous researchers (VEIGA et al., 2016), (PATTIYA, 2011), (BOOG; BIZZO; VALLE, 2007) and (SERRA et al., 1978). However the roots and its residues were not considered at the time as a possible fuel source due to the low agricultural yields that cassava presented in the past. With time, that fact has changed and the necessity to have bioenergy producing bio-fuels is ever greater.

#### **1.4 Objective**

Due to the incessant growth of the world's fuel demand and Brazil's massive and varied biomass production, this work focused on an previously studied biomass that showed promise but was for whatever reason ultimately discarded as a carburant fuel source. The need to expand on the industrial possibilities of utilizing the cassava root as an input for a modern biorefinery and advance the cause of renewable fuel sources in the tropics is its reason to be.

The objective of this dissertation is to establish a proof of concept for a large scale biorefinery that uses the complete cassava plant in order to produce hydrated ethanol, starch powder and surplus electricity. In order to establish that concept, it is necessary to evaluate the technical requirements of mass flow rates, energy consumption and equipment required in both of the industrial processing lines within the biorefinery as well as characterizing the agricultural residue of the cassava plantation as a possible fuel source for the co-generation sector.



## 2 Bibliographic Review

### 2.1 Description of the Cassava Plant ( *Manihot Esculenta Cranz*)

The cassava plant belongs to the Euphorbiaceae family, *Manihot* genus, with *Manihot esculenta* Crantz, having the largest economic impact globally. Known throughout the world by such names as *manioc*, *yuca*, *mandioca*, *macaxeira* and cassava, the cassava plant is presumed to have originated in Brazil, from where it spread to the rest of Latin America and then to Africa, brought about by Portuguese colonizers (GRACE, 1977).

A perennial woody shrub, the cassava plant is mostly planted as an annual crop for its roots, which are an abundant source of low cost carbohydrates for most tropical and sub-tropical regions of the world. Cassava can withstand very poor soils and over all harsher weather conditions, which explains its popularity and economic relevance as the sixth largest agricultural production of the world (GRACE, 1977). The cassava roots accumulate vast amounts of starch which give it its power as a major food source, however, high content of prussic acid or hydrogen cyanide in some of the varieties of cassava roots, create the necessity for previous treatment in order to enable it for consumption (OTSUBO; LORENZI, 2004).

As stated before, the cassava plant can withstand more severe harvest conditions than a lot of crops like corn and sugarcane. Prolonged droughts, soils with low nutrient content and high acidity do not interfere as much with the plants development and growth. However, cassava does require high amounts of sun light and a range of temperatures from 25 to 30 C in order to present its highest performance production wise (LORENZI et al., 2002). The plant structure can be divided in two major sections as it can be seen in Figure 2.1; that which resides above the soil and the subterranean portion. The above-ground section includes the stem, petiole and leaves while the under-ground section includes the roots and of-shoots.

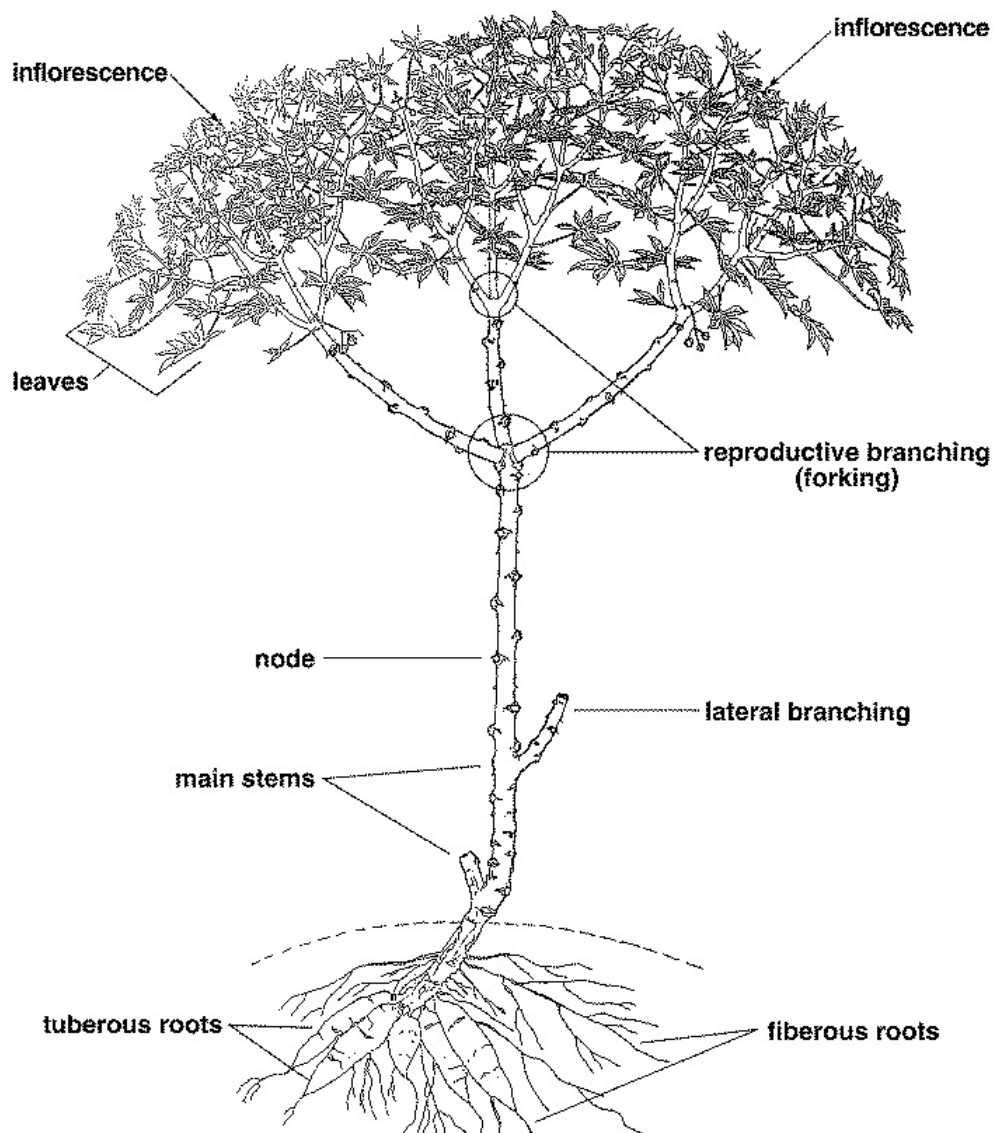


Figure 2.1: Diagram of a cassava plant  
SOURCE: (BOKANGA, 1999)

## 2.2 Productivity of the cassava plant and its harvest

The cassava harvest takes place on average between the months of May and October for the Brazilian Centre/South regions. Usually, root is harvested between 16 to 20 months after the planting of the stems, although the plant can technically be gathered after the first 8 months with a reduced output per hectare and a lower starch content (VEIGA, 2012).

The main steps during the cassava harvest according to (OTSUBO; LORENZI, 2004) are the following:

- Trimming of the branches and leaves at a height of a approximately 25 cm above the

ground.

- Loosening of the soil either with a root extractor or simple blade.
- Extraction of the root from the soil.
- Manual separation of the roots from the remaining stem.
- Collection and transportation of the harvested roots.

The harvesting of cassava cultures is still an immensely labor intensive process since it is mostly a small scale or even subsistence crop. Although there are some varieties of the plant that already possess either partial or complete mechanization (TAKAHASHI; GONÇALO, 2005). Due to this lack of mechanization, the cost of labor during the harvest is disproportionately greater than most other costs.

In Brazil, specifically the mid and southern regions of the country, have had a series of transformations in the harvesting process due to the introduction of the soil softer in 1992. A sort of soil loosener type plow, the soil softer almost completely pulls the root out from the ground, reducing perhaps the most arduous of tasks during the harvest.

Currently, the most mechanized aspect of the complete culture is the initial planting of the stems. (CARVALHO, 2009) states that in the cassava producing regions of Paraná, São Paulo and Mato Grosso do Sul, already use some sort of mechanized planter that however, faces difficulties in dealing with direct planting methods and high density planting schemes. Also, the leaves and branches are currently trimmed with motorized hedge trimmers in order to reduce the intensity of the labor. Harvesters on the other hand are still in little use. According to (TAKAHASHI; GONÇALO, 2005), a partnership between a private producer and the Yoki/Indemil Group, began to manufacture a prototype harvester especially for cassava in the year 2000. However, due to problems during harvesting the project was deemed unfeasible. The year 2004 saw a rebirth in the attempts to fully mechanize the cassava harvest with a project between the Cassava Producers Association of Brazil or ABAM in Portuguese and the Hennipman Company. This new harvester mixed a potato harvester with modifications made to the failed previous harvester. An example of a cassava root harvester can be seen in Figure 2.2. In their book "*A Cultura da Mandioca*", Takahashi states that this harvester presented an efficiency of 96% in comparison to an efficiency of 94% during manual harvest in sandy porous soils. The cost of harvest per ton was of R\$3.50 - 8.00 in 2005 R\$ depending on the area and region. Despite this, the cassava harvest remains, on a national average, a highly manual task.



Figure 2.2: Hennipman root harvester  
SOURCE: (HENNIPMAN, 2016)

After the up-rooting of the plant, the roots are separated from the stem manually and placed in big bags that can hold weights of up to 700 kg in order to facilitate their transport either directly to market or any other industrial facility for post processing. In some cases however, the roots are thrown by hand into a truck bed.

Most literature in agricultural journals on cassava productivity give detailed accounts on root productivity per hectare for different strands of the cassava plant. However, due to the relevance of residue usage to a complete and modern biorefinery, the amount of biomass residue derived from the harvesting of the cassava plant becomes an important factor in the final choice of cassava strand. Table 2.1 contains some examples of studies that do deal with cassava crop residue. This information was gathered from authors both from Brazil and Thailand. Most of these studies do not utilize a uniform harvesting time and of course even with these same strands, the residue to roots ratios would vary depending on location, crop duration and even weather conditions. Yet, Table 2.1 does provide us with an initial estimate that would guide the choice of strand, a choice that would not only take into consideration a basic agricultural output indicator.

Table 2.1: Agronomic parameters of root and residue productions for various specimens in dry base

Author	Specimens	A	B	A/B	Harvesting Months
		Roots T/ha	Areal Section (T/ha)		
(MOURA; COSTA, 2001)	Metro III	16.73	24.26	0.69	18
	Paxiúba II	21.44	26.32	0.81	
	Pretinha	20.94	20.08	1.04	
	Pirarucu	18.53	18.47	1.00	
	Paxiubão	14.43	12.53	1.15	
(LORENZI et al., 2002)	Espeto	12.32	6.03	2.04	12
	Fécula Branca	14.85	9.25	1.61	
	IAC 13	8.41	10.33	0.81	
	IAC 14	9.75	15.37	0.63	
	IAC 15	11.63	8.26	1.41	
(PATTIYA, 2011)	-	-	-	1.73	-
(VEIGA et al., 2016)	IAC 90	8.48	4.18	2.03	12
	IAC 14	13.04	9.21	1.41	
	48/98	11.94	6.52	1.83	

### 2.3 Industrial processing of the cassava root : ethanol and starch production

The use of the cassava root for the production of both starch and ethanol has found its place in the industrialization processes of many emerging economies. Countries like China and Thailand are world references through the use of cassava root for the production of most of their ethanol, while other countries in Africa and Latin America have started to increase production of cassava ethanol while industrializing their starch productions. Brazil is no different, with its historic starch production at an industrial scale, there are many factories all around the country that produce large amounts of starch to be used throughout the Brazilian food industry.

Primarily, (SALLA et al., 2010) describes the industrial process required to produce ethanol from tuberculous starchy sources, while Vilpoux 1999 describes the process of starch extraction for food-stuff from the cassava root. Following, are the detailed steps within the planned factory that will transform the cassava roots into either fuel ethanol or starch powder or both. Figure 2.3 presents the basic processes that take place within the industrial sector of the biorefinery in order to produce ethanol and starch powder. With the different processes explained in further detail subsequently.

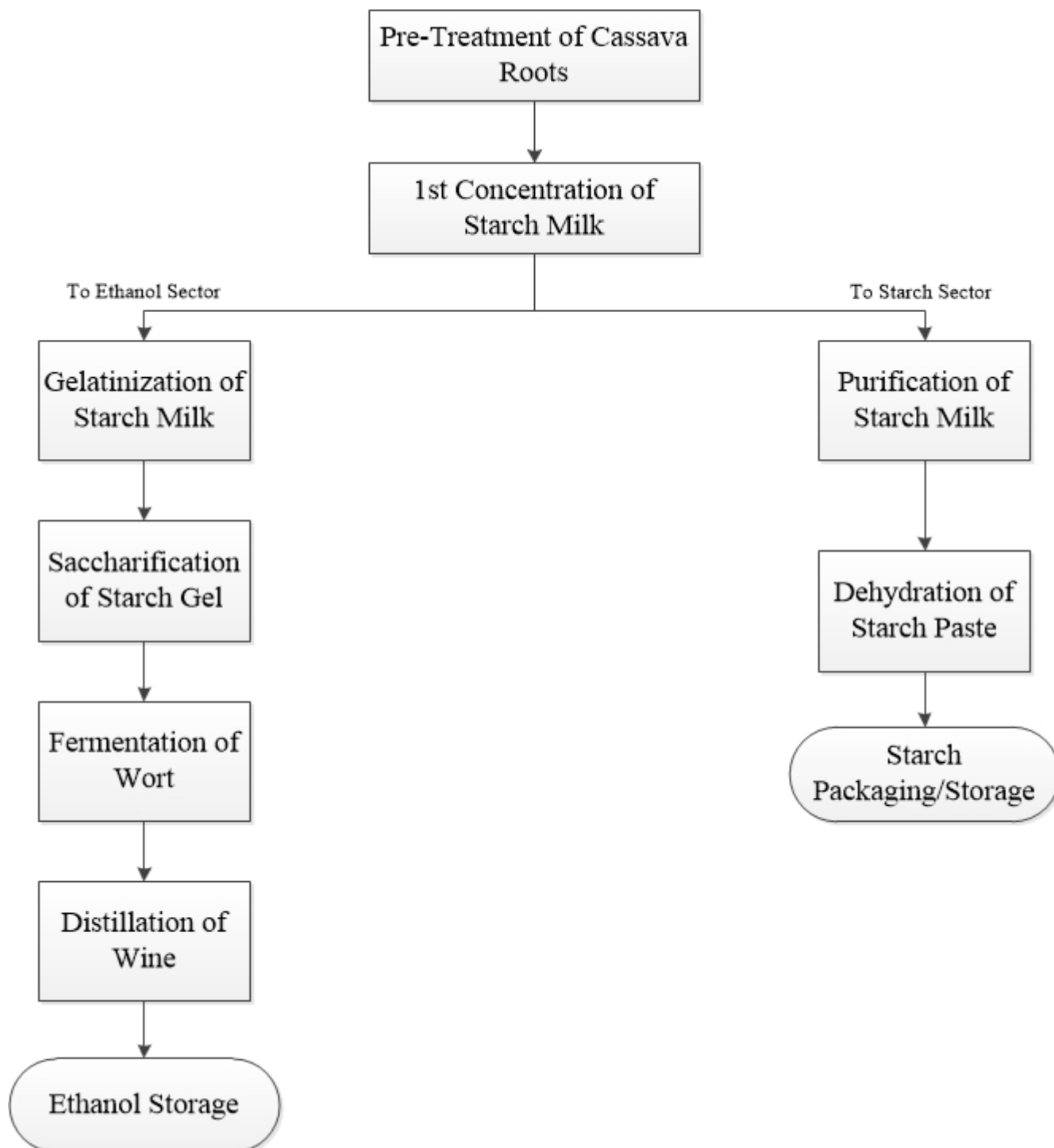


Figure 2.3: Processes structure of the biorefinery

### 2.3.1 Pre-treatment of the biomass: cleaning, grating, and concentration of the starch milk

In order to properly process the cassava roots, whether for ethanol production or starch extraction, the first step of the entire endeavour is to properly treat the roots. As the biomass

is received and weighted a hydraulic platform and collector assists in the displacement of the roots into a storage deposit. It must be noted the great importance in the processing of the *in-natura* root within 48 hours of harvest in order to prevent the deterioration of the starch molecules within. If not, steps can be taken in order to turn the root into a more durable biomass, such as slicing the roots into fine chips and drying them in the sun as it is done in Thailand (FERREIRA-LEITAO et al., 2010).

From here, the cassava roots are carried through a screw conveyor onto a vibrating screen in order to remove excess dirt and stones that have been brought with the roots from the extraction process. According to (LEONEL; JACKEY; CEREDA, 1998), after this step the roots are taken through a washer and peeler, where constant streams of water and peeling blades drag the roots at controlled speed carefully removing the roots fine protective skin and preserving the starch content as much as possible. Any leftover soil and rocks are also removed during this washing process.

Vilpoux 1999 describes the final step of the pre-treatment, in which the roots are cut into pieces 2 to 5 cm in length in order to facilitate the grating process. In the grater, a dosing screw feeds the equipment at a constant rate in order to augment productivity while a high speed rotating cylinder grates the cut roots, breaking apart cell walls ensuring the liberation of the starch within the cell. Here, both the free starch and the starch from inside the cell walls are made readily available. An example of an industrial root grater can be seen in Figure 2.4.



Figure 2.4: Cassava root industrial grater  
SOURCE: (EBS, 2017)

As water is added in counter flow, the extraction of the starch milk is done through batteries of high speed conical sieves with gradually diminishing openings from 250 to 125  $\mu\text{m}$ . According to Vilpoux 1999, most centrifuges throughout the Brazilian industrial complex utilize rotations of up to 1200 RPM and motors of 15 HP in order to properly extract the starch. In

comparison, Thai starch factories use centrifuges of 800 RPM and 7.5 HP. These sieves, remove the main bulk of fibrous residues or bran.

The starch milk, however, still contains many impurities, mainly micro-fibers that have not been able to be extracted through the centrifuges, proteins and vegetable fats, and a great deal of water that must be removed in order to purify and concentrate the starch milk.

With the extraction of the starch milk from the main production line, the bran goes through dry presses composed of infinite screws, conveyor belts or even complementary centrifuges in order to reduce the humidity within the bran from 90% to as low as 40%, although it would require further drying in order to ferment the starch within the bran. According to Leonel 2000, this bran can still be utilized for the extraction of residual starch and its subsequent fermentation through theoretical enzymatic processes, aside from the usual uses as animal feedstock.

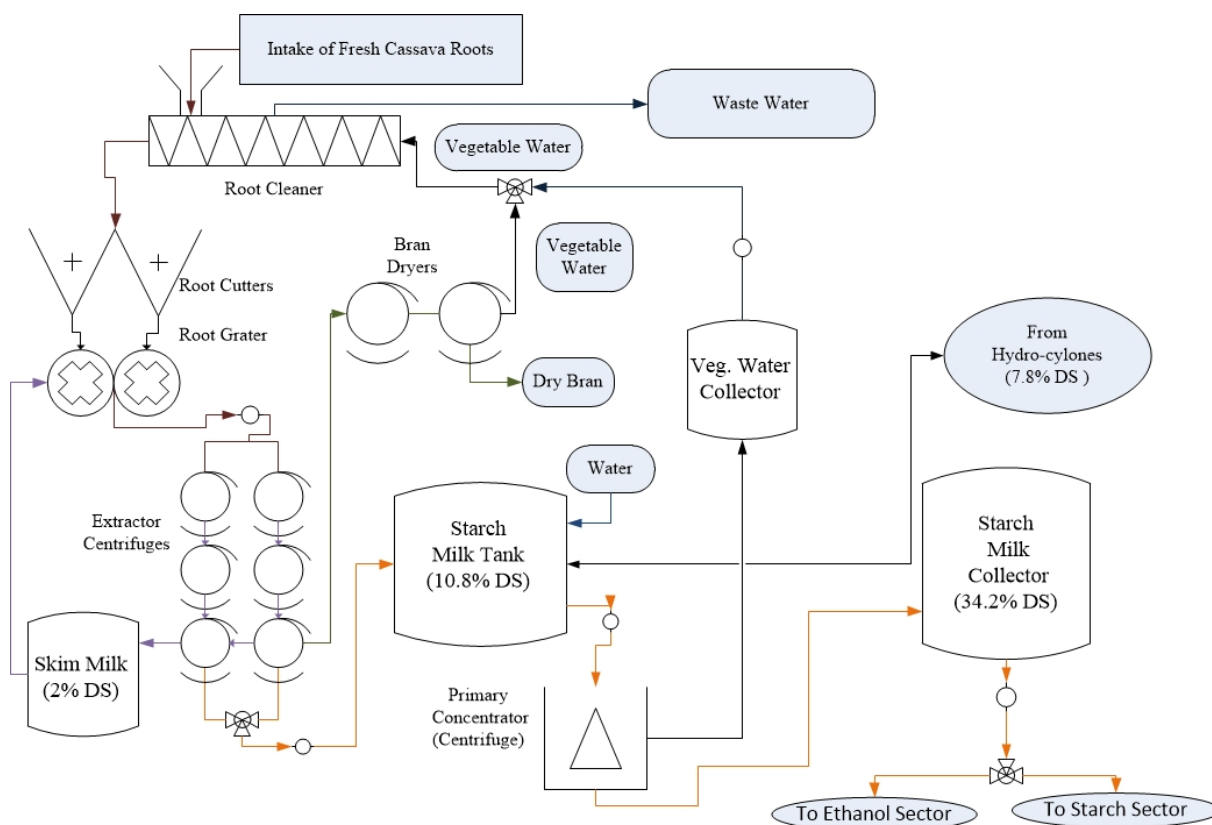


Figure 2.5: Pre-treatment of roots: cleaning ,grating and concentration of milk

In order to continue with either the process of fermentation for ethanol production, or starch extraction, the starchy milk must be concentrated. In the case of ethanol, according to (OLSEN, 1995), a concentration of 30 to 40% of dry starch or DS, is necessary in order to achieve a proper gelatinization of the starch particles, while the concentration helps reduce the amount of impurities for the consumable starch production. In Brazil, the starch milk is be put through a centrifuge, entering at approximately 3 to 4 Baume<sup>1</sup> and exiting at 15 to 18 Be°. The

<sup>1</sup> 1 Baume (Be°) = 1.75 Dry Starch (DS) = 1.8 Brix (Br°)



water extracted from this centrifuge is utilized in the washing and pre-treatment of the roots. Consequently, 18 Be° is about 31% DS, according to the International Starch Institute, meaning that after the concentration process the streams for ethanol and dry starch production can be split on to two separate sectors. The schematics of the pre-treatment process can be seen in Figure. 2.6.

The residual organic solid matter can be utilized in various forms. Vilpoux 1999 suggests that the matter be transformed into organic fertilizers that could be spread out on the fields in order to assist with the nutritional renewal of the soil, especially if the leaves and branches would be removed and taken to the refinery for their subsequent combustion in order to produce energy.

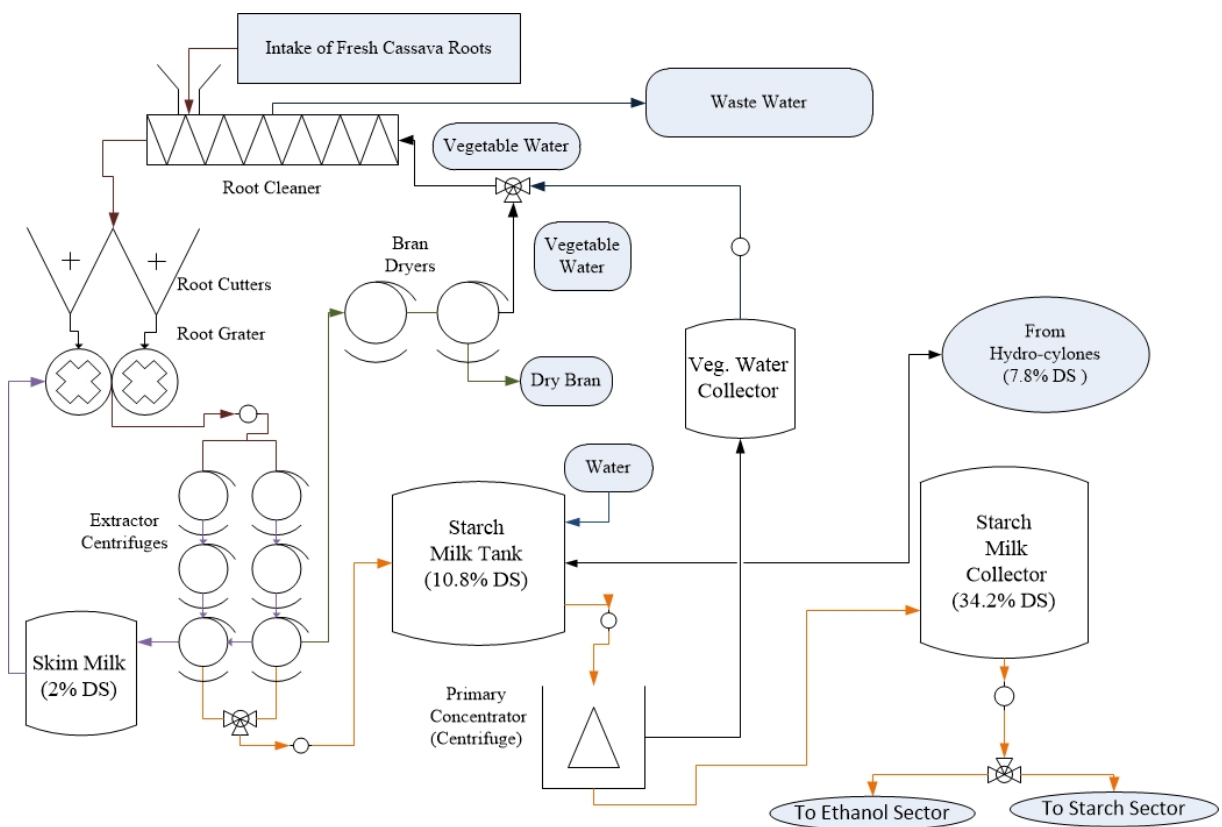


Figure 2.6: Pre-treatment of roots: cleaning ,grating and concentration of milk

### 2.3.2 Purification of the starch milk

Here is where the starch extraction for powdered starch production begins. As stated before, the starch milk is concentrated using a centrifuge that pumps out a milk with approximately 15 to 18 Be°. This milk is then passed through a series of micro hydro-cyclones in order to remove any and all impurities from the milk. In these cyclones, milk is pumped at high speed in order to form a vortex that pushed heavier particles against the cyclone walls and expels them

from the bottom end of the equipment. The milk and smaller particles form a second vortex that exists from the upper end of the cyclone only to enter another, smaller, cyclone. A diagram of how a hydro-cyclone functions can be seen in Figure 2.7.

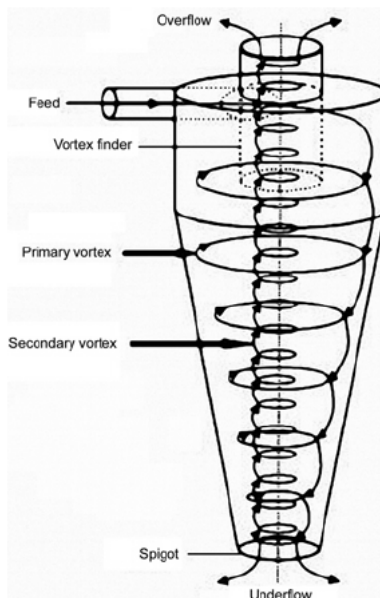


Figure 2.7: Schematic diagram of a hydro-cyclone

Clean water is mixed with the milk, decreasing its concentration to 5 or 6 Be° at the intake of the battery of cyclones only to be extracted with a concentration of 24 Be°. The water removed from the purified milk is reused within the factory, both in the grating processes and initial starch extraction (VILPOUX, 1999). From here on out, the milk basically needs to be dried and packaged before being shipped out to consumers.

### 2.3.3 Dehydrating and packaging the starch powder

The concentrated starch milk exits the purifier centrifuge and enters what is called a concentric basket centrifuge or peeler, that extracts approximately 65 % of the water. In Brazil, according to (VILPOUX, 1999), most starch factories utilize a vacuum filter that is fed at a constant rate in order to extract humidity. However, this method is less efficient than the peeler as it only removes about 10% less excess water off the starch paste. The vacuum filter is less expensive and consumes less energy, but overall, the benefits of the peeler have a greater impact in the expenses of energy during the final drying process. Less water in the paste also means that the paste is allowed to be exposed to higher temperatures without incurring in a greater risk of gelatinization of the quasi finished product. In the case of most Brazilian starch factories, where vacuum filters are used, dry powder must be mixed with some wet paste in order to decrease the overall humidity of the paste so that it can be properly dried off, turning the drying process into

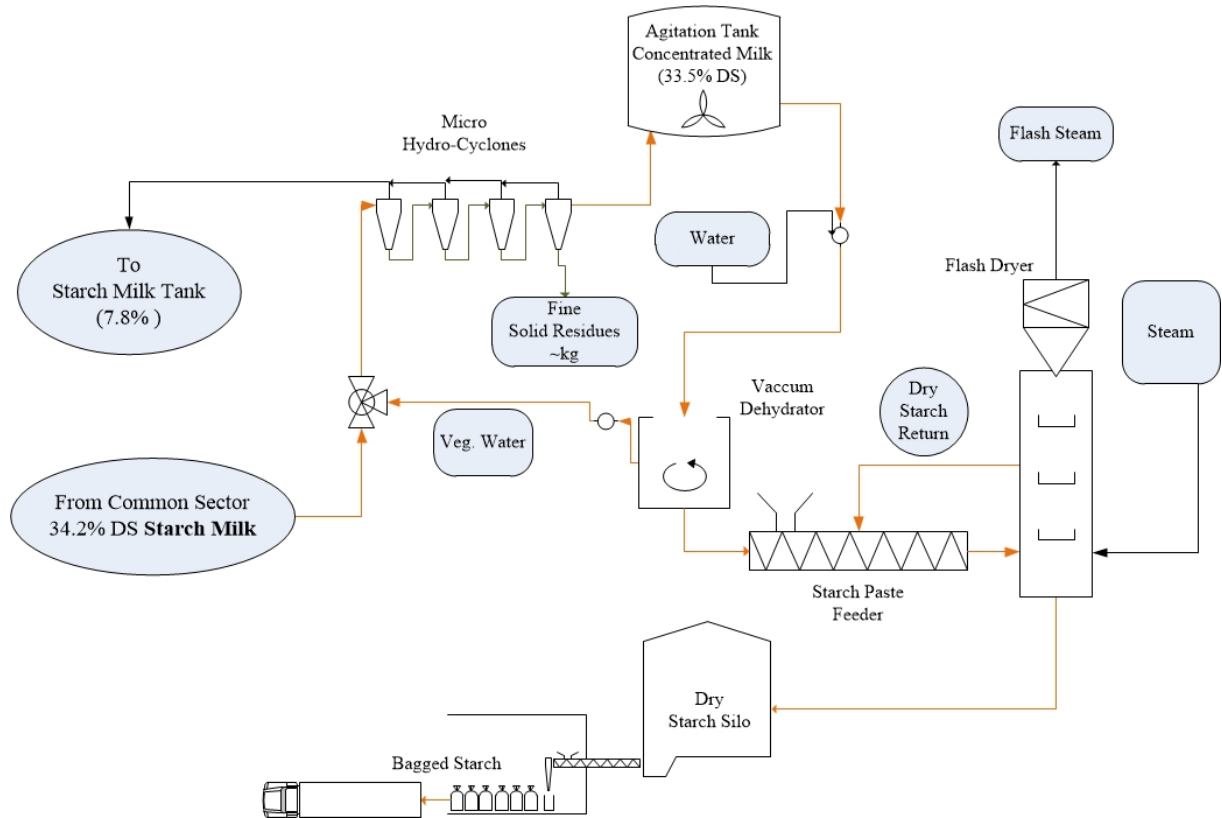


Figure 2.8: Starch production sector of cassava mill

a longer two-step process.

After the centrifuge, the resulting paste is sent through a screw conveyor, for drying and packaging after the peeler. In order to efficiently dry the starch paste into a fine powder, the process utilizes a flash steam dryer. According to (GERALDI, 2006), in the flash dryer the paste is mixed with a stream of hot air at 150°C coming from steam heat exchangers that enables a final humidity between 12 and 13%. The starch powder is separated from the air stream through cyclones that also guarantee some granular homogeneity in the starch powder. The final product is now only at an approximate 58°C and is ready for bagging.

(VILPOUX, 1999) states that in the drying and packaging process there is a loss of approximately 4% of finished starch powder.

### 2.3.4 Gelatinization and saccharification of the starch wort

As stated before, in order to begin the process of fermentation it is necessary to transform the starch milk into a fermentable wort. This process is called hydrolysis. The concentrated starch milk is first cooked in the presence of heat-stable  $\alpha$ -amylase enzymes. Since starch is made up of two polysaccharides: Amylose and Amylopectine. Amylose is formed by a linear chain of  $\alpha$ -D-Glucose joined by glycosidic bonds while Amylopectine is formed by small and

branched chains of Glucose (RIBEIRO; SERAVALLI, 2007). The  $\alpha$ -amylase enzymes hydrolyse their corresponding  $\alpha$ -1,4-glycosidic bonds in the gelatinized starch, lowering the viscosity greatly (OLSEN, 1995). This initial gelatinization creates "maltodextrins" that need to be broken down into fermentable sugars. The wort is then placed into a stirring tank to guarantee homogeneity. From this tank it is pumped through a regenerator, heating it up from approximately 32 to 65°C using a counter flow of wort exiting the dextrinization tank.

citeOlsen1995, indicates that in order to properly gelatinize the starch particles so that enzymes can be used to break up the carbohydrates that make up the starch, a jet cooker using pressurized steam is used to “cook” the wort up to 105°C where a series of tubes guarantee a residence time of 5 minutes, after which a flash tank lowers the temperature of the wort to 95°C. Figure 2.9 and Equation 2.1 represent the gelatinization mechanism that the starch goes through in order to become digestible complex sugars.

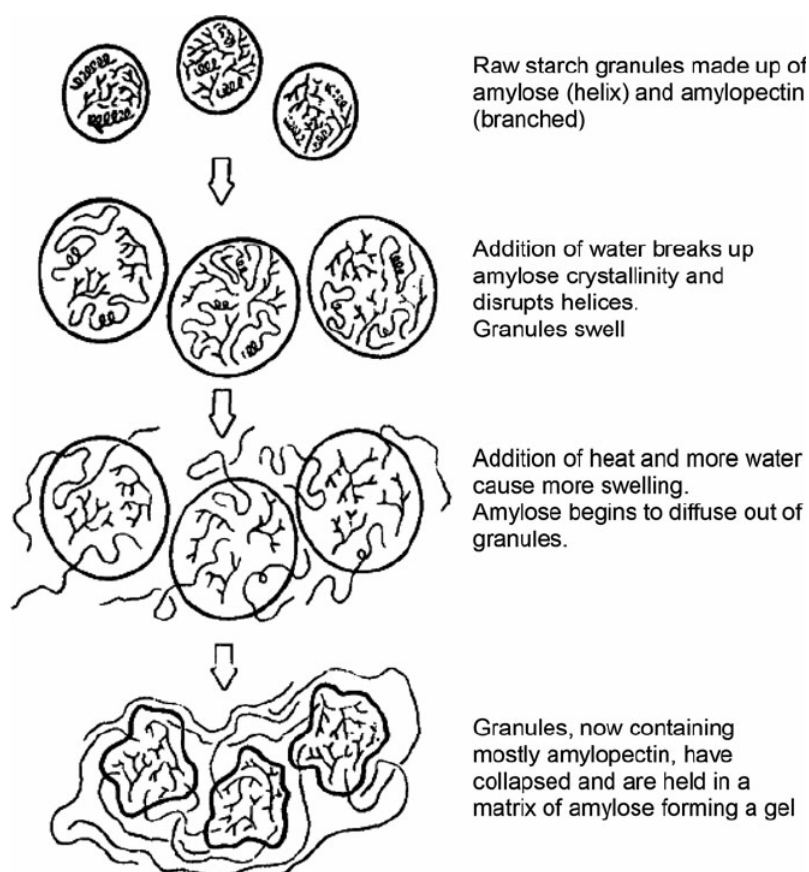
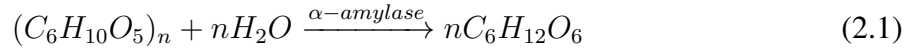


Figure 2.9: Starch gelatinization mechanism

SOURCE: Reproduced from (REMSSEN; CLARK, 1978)

From here, the wort is pumped to a stirring tank where the process of dextrinization is allowed to occur with a residence time of 2 hours in the tank. Followed by a pass through the regenerator in order to bring the temperature of the wort down to 65°C and into a saccharification tank that will guarantee the source of nutrients required by the *Saccharomyces cerevisia* yeasts that is responsible for the alcoholic fermentation resulting in ethanol in future steps.



In the saccharification tank, the warm wort is mixed with water and glucoamylase and maltoamylase enzymes that will catalyse the transformation of the unfermentable dextrans in the wort into glucose and other fermentable sugars (OLSEN, 1995). Enough water is introduced to achieve a saccharification yield of 18.5 Br°, which is a typical density used in the sugar cane ethanol refineries of Brazil. The total residence time in the saccharification tank is 24 hours and after the total transformation of the starch milk into a fermentable wort, the wort is pumped through a heat exchanger in order to decrease its temperature from 65 to 32°C, finally preparing it for fermentation.

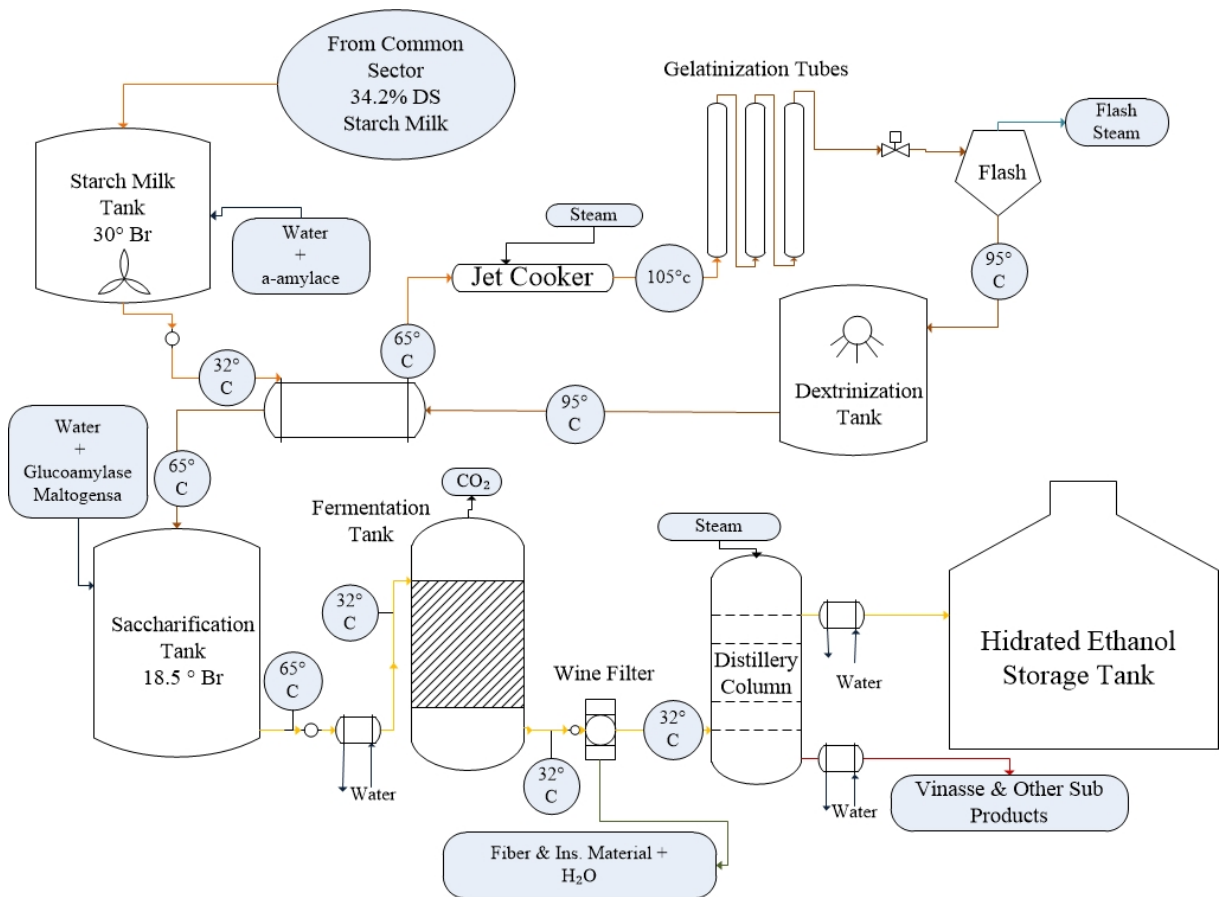


Figure 2.10: Ethanol production sector of cassava mill

### 2.3.5 Fermentation and distillation of the cassava ethanol

After the saccharification process is completed, the former starch milk is now a wort that can be properly fermented. Fermentation can occur in two possible methods according to (Venturini Filho; MENDES, 2004), by continuous fermentation or by batches. In both methods the

wort is mixed with an innocuous mixture of *saccharomyces cerevisiae* that will allow the reproduction and multiplication of the yeast in the wort. In the continuous method, the wort is run through a series of fermentation dorns in order to allow the complete fermentation of the sugars present in the wort, generally this method is faster than batch fermentation, however as the yeast must be recirculated within the system in order to guarantee an optimal concentration level, the risks of yeast contamination are greater (CAMACHO, 2009). Usually, ethanol producers stick to the simple batch fermentation. Tried and tested since prehistoric times, the wort is let to sit fermenting in a dorn while both temperature levels and brix attenuations are monitored in order to signalize the completion of the fermentation process. Then, the now wine is pumped through a centrifuge that separates the spent and/or dormant yeast cells. The yeast is cleaned through acidic chemical treatments in order to kill off any unwanted bacteria and is then reused in the next batch (PAPAZIAN, 2003). The wine on the other hand is sent to the distillation column.

In the distillation column, the ethanol will be separated from the fermented wine. Here, water, ethers, aldehydes, organic acids, fuzel oils and other secondary components are separated from the ethanol (Venturini Filho; MENDES, 2004). Solids that managed to pass through the centrifuge are also removed, mainly suspended yeast, bacteria, mineral salts, non-fermented sugars and non-fermentable sugars as well. Yet, unlike sugar cane wort, the wort made from starch milk usually contains less contaminations and by products after fermentation. The intense filtrations that were previously made and the fact that there are less non-fermentable sugars present in the wort create a wine with less vinasse than other sources of sugars.

The distillation column is a simple concept with heavy engineering and design in order to guarantee the most amount of residue separated from the ethanol. The column is built with a series of trays that function as small distillation boilers. Generally, these trays are fed with wine and steam at 127.4°C and 2.5 bar in order to evaporate the unwanted components of the wine. The vapours rise through the trays and each component is separated by their differences in volatilization temperatures. The initial fractioning of the liquid faces within a distillation column is called the "brute" alcohol and has an ethanol content that varies from 50 to 94 °GL (CAMACHO, 2009). This "brute" alcohol is cooled and the remaining vapour condensates in refrigeration towers so that it can be rectified in a second smaller column, removing the last volatile impurities and leaving a hydrated ethanol of approximately 97.5 °GL.

## 2.4 The cassava energy balance

This section deems to present the energy expenditures of both of the processes that the proposed biorefinery would partake in. Table 2.2 contains the total energy consumption of the complete transformation of fresh cassava roots into ethanol. (VEIGA et al., 2016); (SALLA et al., 2010); (DAI et al., 2006), present us with up to date consumption figures that allows to

see some gains in efficiency in the case of Veiga and Salla (both from Brazil) and the variations in energy costs between countries. In all three cases, the most energy intensive processes are cooking and distillation, both of which require mostly thermal energy in the form of steam. The total energy consumption per ton of finished product is an information that will permit the analysis of optimal flows for the biorefinary.

Table 2.2: Total energy consumption in MJ per ton of ethanol

Sector	(VEIGA et al., 2016)		(SALLA et al., 2010)	(DAI et al., 2006)
	Electricity	Heat		
Pre-Treatment	120	0	-	-
Grinding	341	0	280	110
Cooking, liquefaction and saccharification	86	982	8,365	1,605
Filtration	-	-	-	2,210
Fermentation	225	0	75	150
Distillation	116	8,800	6,145	5,115
Other	-	-	40	-
Total by type	888	9,782	-	-
Total		10,670	14,905	9,190

In the case of starch production, few studies exist on the energy consumptions of modern and industrial starch factories. (CHAVALPARIT; ONGWANDEE, 2009), divide the expenditures of a Thai starch factory not by process but merely by type of energy required, signalling again that the highest process requirement is for thermal energy that in his case study came from burning bunker oil in order to generate steam. (TRAN et al., 2015) on the other hand, presents a thorough comparison between large-scale starch productions in Thailand and southern Vietnam and some small-scale, almost artisanal, starch productions in Colombia. Table 2.3 includes the energy expenditures per ton of starch produced for the large-scale projects. (TRAN et al., 2015) signals that the largest energy expenditure is the starch drying process (approximately 81%) which not only involved thermal costs but also electric.

Table 2.3: Total energy consumption in MJ per ton of starch.

Sector	(TRAN et al., 2015)	(CHAVALPARIT; ONGWANDEE, 2009)
Pre-Treatment	15.4	-
Rasping	164.2	-
Extraction	181.0	-
Purification	118.8	-
Drying(Elec)	102.2	-
Drying(Therm)	1945.0	-
Other	1.2	-
Electric	-	608 ± 135
Thermal (fuel)	-	1303 ± 324
Total	2527.8	1911 ± 351

As these two different productions, ethanol and starch, do share some processes it will be interesting to learn how the variation of input mass will affect the different energy expenditures. As some processes overlap, especially during the pre-treatment of the roots and initial extraction of the starch, the most energy intensive treatments (distillation for ethanol and drying for starch) will play a significant role in determining the final output of the biorefinaries electric generation. In any sense it does come to light that the production of starch does really represent a lesser energy expenditure whether it be thermal or electric than that of the ethanol production.

## 2.5 Biomass co-generation in Brazil

The Brazilian energy production sector currently has 4,915 power generators that utilize the various primary energy sources available (hydro, nuclear, eolic, solar, thermal, etc. ) producing an approximate of 158.183 TW of power (ANEEL, 2018). In the next few years, the generation capacity is expected to grow by 18 TW through 222 projects already under construction and 376 in the processes of licensing.

Qualified cogeneration plays a smaller scheme in system which mostly depends on hydroelectricity. Approximately 2.67% of the total amount of installed power are considered true heat and power plants (ANEEL, 2018). These are the plants that the generation of both heat and power is not utilized completely by the industrial process to which it is connected to (ANEEL, 2015).

However, practically all thermal generation units that run on some sort of renewable/residue energy, are cogeneration plants. In this sense, biomass generators account for 9.3% of the total installed power (ANEEL, 2018) while agroindustrial residue generators with 481



production units (sugar cane bagasse, rice husks, etc.) represents 77.49 % of the installed capacity of biomass generation (ANEEL, 2018). Table 2.4 present the installed capacity of the different agro-industrial residues that have installed co-generation capacities in Brazil

Table 2.4: Agroindustrial cogeneration installed capacity  
SOURCE: (ANEEL, 2018).

Primary Source	Generation Units	Installed Power (kW)	%
Sugar Cane Bagasse	402	11,297,670	99.31
Rice Husks	12	45,333	0.4
Biogas	2	948	0,01
Elephant Grass	2	31,700	0.28
Total	418	11,375,651	100

## 2.6 Characterization of biomass for fuel purposes

In order to develop an adequate combustion project to generate energy through the burning of the cassava plant residues, both the chemical and physical characteristics of the biofuel must be known thoroughly. This contributes to the information necessary to properly handle both solid and gaseous residues derived from combustion, while also enabling to properly dimension the equipment necessary for the task at hand (JOSÉ; BORK, 2011). Most analysis deemed necessary within the studied literature include:

- Proximate and Ultimate Analysis, including both Chlorine and Sulphur
- Gross and Net Calorific Value for the Fuel
- Ash Fusion
- Thermo-gravimetric Analysis

### 2.6.1 Proximate chemical composition and ultimate analysis

A proximate analysis constitutes in determining moisture content, ash content, volatile matter and by a difference, fixed carbon within the biomass. The moisture levels recorded in a proximate analysis are both free moisture held by the biomass and inherent water retained in pores in the material.

Both ash and volatile matter can only be identified as a whole using the proximate analysis, so in order to determine the actual components of the ash and volatile matter portions of the biomass, other analysis would need to be used. Volatile matter in biomass is transformed in to an equivalent heat transfer for the combustion process. Ash, on the other hand, is made

up of many trace elements while calcium, phosphorous, potassium and magnesium are the key elements present. The fixed carbon that remains in the biomass after the volatility of the fuel has ended is calculated by subtracting the resulting moisture, ash and volatile matter content as mass fractions from 100 and can be used through a ration of fixed carbon and volatile matter as a measurement of combustion reactivity and burnout (LOO; KOPPEJAN, 2008).

The ultimate analysis on the other hand determines the relative values of the main constituting elements of the biomass. Basically, the fuel is broken into its carbon, hydrogen, nitrogen, sulphur and oxygen portions, while newer tests also determine the amount of chlorine contained inside the bio-fuel due to its high corrosive properties.

Both of these analysis are important to determine the mass and energy balances of the combustion system. In (JENKINS et al., 1998), one can find data sets of proximate and ultimate analysis for many different sorts of biomass studied and utilized throughout the world. Tables 2.5 and 2.6 has but some of the most common examples that Jenkins presents to us.

Table 2.5: Proximate analysis of various biomasses in mass percentage (%)

SOURCE: (JENKINS et al., 1998) and (VEIGA et al., 2016)

	Wheat Straw	Rice Hulls	Rice Straw	Switch-grass	Sugar cane Baggasse	Cassava Plant Residue
Fixed Carbon	17.71	16.22	15.86	14.34	11.95	11.22
Volatiles	75.27	63.52	65.47	76.69	85.61	85.87
Ashes	7.02	20.26	18.67	8.97	2.44	2.91

Table 2.6: Ultimate analysis of various biomasses in mass percentage (%)

SOURCE: (JENKINS et al., 1998) and (VEIGA et al., 2016)

	Wheat Straw	Rice Hulls	Rice Straw	Switch-grass	Sugar cane Bagasse	Cassava Plant Residue
Carbon	44.92	38.83	38.24	46.68	48.64	42.64
Hydrogen	5.46	4.75	5.20	5.82	5.87	6.25
Oxygen	41.77	35.47	36.26	37.38	42.82	47.21
Nitrogen	0.44	0.52	0.87	0.77	0.16	0.79
Sulphur	0.16	0.05	0.18	0.19	0.04	<0.2
Chlorine	0.23	0.12	0.58	0.19	0.03	<0.3

## 2.6.2 HHV and LHV analysis

Although equations can be used to approximate the High Heating Value (HHV) and the Low Heating Value (LHV), most HHV's are determined through simple standardized tests that allow us to know the exact amount of energy released by the complete combustion of the

biomass. In order to determine the LHV, the amount of energy needed to vaporize the water content of the biomass and that which results from the oxidization of hydrogen molecules during the combustion, must be subtracted from the HHV. So, the LHV varies according to both the moisture content and hydrogen content of the fuel at the time of combustion of the material, making it a proper tool to determine the "useful" energy content of a fuel during a general industrial application (JENKINS et al., 1998). Also in this subject, Jenkins provides us with the HHV of various examples of biomasses, which are shown in table 2.4.

Table 2.7: HHV of various biomasses

SOURCE: (JENKINS et al., 1998) and (VEIGA et al., 2016)

	Wheat Straw	Rice Hulls	Rice Straw	Switch-grass	Sugar cane Bagasse	Cassava Plant Residue
MJ/kg	17.94	15.84	15.09	18.06	18.99	17.21

### 2.6.3 Thermo-gravimetric analysis

This analysis consists of measuring the mass of a given bio-fuel as a function of temperature and time. This test can be done in controlled atmospheres, both oxidizing and inert, in order to better understand the process of combustion of the biomass, mainly the temperatures at which the loss of volatile matter initiates, the temperatures of formation and oxidation of fixed carbon, and the ignition temperature of the material as used by (GROTKJÆR et al., 2003). Through a qualitative analysis of this information, the composition of the biomass, can be partially determined (JOSÉ; BORK, 2011).

In Figures 4.3 and 2.12 we can see examples of a TGA analysis of sugar cane bagasse and its derivative, which measures the rate at which mass is lost at any given temperature.

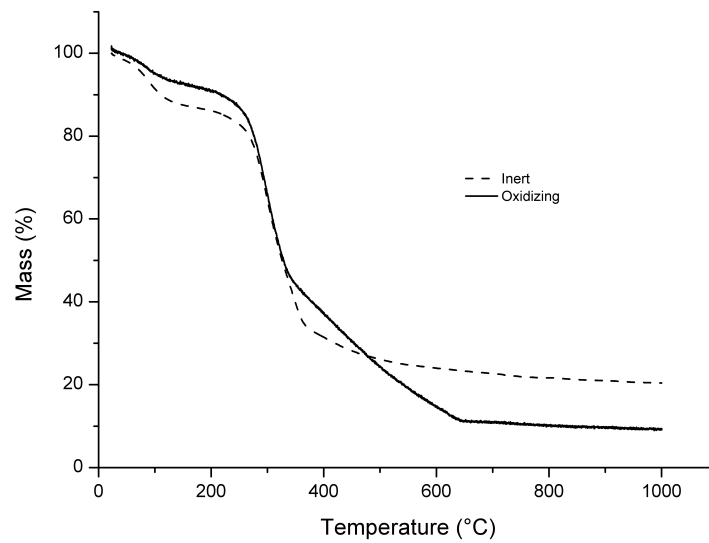


Figure 2.11: TGA curves for the IAC 14 variety of cassava for oxidizing and inert atmospheres (seed stem and thick and thin stalks in equal parts)  
SOURCE: (VEIGA et al., 2016)

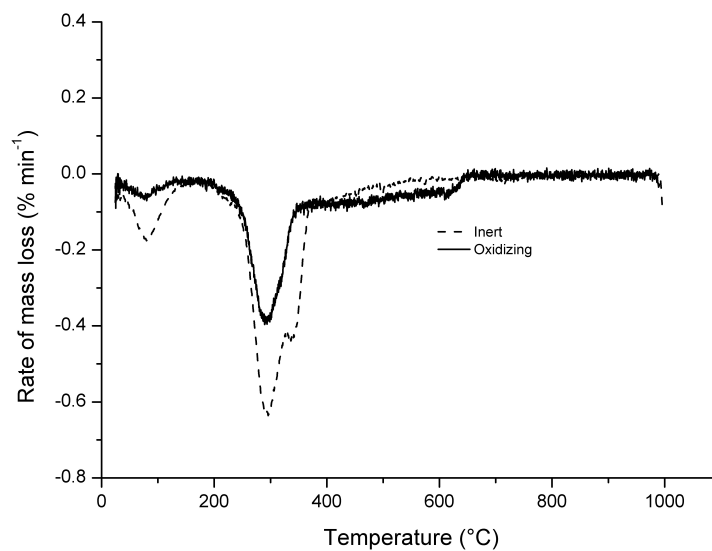


Figure 2.12: DTG curves for the IAC 14 variety of cassava for oxidizing and inert atmospheres (seed stem and thick and thin stalks in equal parts)  
SOURCE: (VEIGA et al., 2016)

#### 2.6.4 Ash fusion analysis and its relevance

The problems associated with ash production through the burning of biomass are one of the utmost importance for those that work with the combustion of any biomass. As bio-masses are known to contain different compositions of ash residue, these ashes can present troubles of such size and plenitude that biomass operating systems can lose thermal efficiency, become non-operational, and to some extent lead to the destruction of the industrial equipment. Fouling, slagging, sintering and high temperature corrosion caused by fused ash deposits, make it ever so important for a planner and operator to know the main composition and quantity of ashes within a certain biofuel.

Silica, potassium, sodium and phosphorous are some elements that when present in high quantities can cause viscous deposits inside boilers when they have reached their melting temperatures (MILES et al., 1996). The presence of silica by itself is not a problematic situation, seeing that  $\text{SiO}_2$  has an elevated fusion temperature (above  $1650\text{ }^\circ\text{C}$ ). However, alkali metals have the capacity to cause ruptures in the bonds of the silica's anionic structure, substituting those Si-O-Si bonds, by Si-O-M where M represents a cation of alkali metals such as potassium or sodium. Alkali metal silicates have relatively low fusion temperatures (less than  $750\text{ }^\circ\text{C}$ ) and contribute to the overall ash fusion temperature to become lower (TEIXEIRA, 2012); (PAULRUD, 2004); (BAXTER et al., 1998); (THY et al., 2006). These low fusion temperatures and the technical difficulties brought on by them can be estimated through correlations of mass fractions between basic oxides and acid oxides that constitute the ash particles which are summed in the alkaline index of ashes (MILES et al., 1996); (LLORENTE; GARCÍA, 2005); (LLORENTE; GARCÍA, 2006); (PRONOBIS, 2005); (PRONOBIS, 2006); (JOSÉ; BORK, 2011).

Again in table 2.8, (JENKINS et al., 1998) presents the composition of the ashes of various bio-masses and their alkaline indexes while (VEIGA et al., 2016) presents the data for the cassava residue.

Table 2.8: Ash composition and alkali index of various biomasses  
 SOURCE: (JENKINS et al., 1998) and (VEIGA et al., 2016)

	Wheat Straw	Rice Hulls	Rice Straw	Switch-grass	Sugar cane Bagasse	Cassava Plant Residue
Elemental Analysis of Ashes (% mass)						
$SiO_2$	55.32	91.42	74.67	65.18	46.61	3.44
$Al_2O_3$	1.88	0.78	1.04	4.51	18.99	2.40
$TiO_2$	0.08	0.02	0.09	0.24	2.63	0.14
$Fe_2O_3$	0.73	0.14	0.85	2.03	14.14	1.32
$CaO$	6.14	3.21	3.01	5.60	4.47	21.76
$MgO$	1.06	<0.01	1.75	3.00	3.33	13.77
$Na_2O$	1.71	0.21	0.96	0.58	0.79	0.28
$K_2O$	25.60	3.71	12.30	11.60	0.02	26.43
$SO_3$	4.40	0.72	1.24	0.44	2.08	3.54
$P_2O_5$	1.26	0.43	1.41	4.50	2.72	25.43
Alkali Index (kg/GJ)						
AI	1.07	0.50	1.64	0.60	0.06	0.46

(MILES et al., 1996), however, states that for biomass with an alkali index between 0.17 and 0.34 kg/GJ there is a medium risk of the occurrence of fouling. Above 0.34 kg/GJ on the other hand, the risk of ash deposition is imminent so proper maintenance and care must be taken into account in order to protect the high temperature components of the boilers. The equation for the Alkali Index as given by Miles is the following:

$$AI = \frac{10^6}{HHV} Y_a (Y_{K_2O} + Y_{Na_2O}) \quad (2.2)$$

- AI - Alkali Index.  $\left(\frac{kg}{GJ}\right)$
- HHV - High heating value of the fuel  $\left(\frac{kJ}{kg}\right)$ .
- $Y_a$  - Mass fraction of ash in fuel.
- $Y_{K_2O}$  - Mass fraction of Potassium Oxide within the ash.
- $Y_{Na_2O}$  - Mass fraction of Sodium Oxide within the ash.

This index is a quick and easy measurement of the probability of the formation of ash deposits and incrustations on the walls of boilers, although as (MILES et al., 1996) points out, it was not constructed for biomass ash deposits, so it is more of an indicator of possible ash difficulties more than an exact characterization result.

## **3 Methodology**

### **3.1 Characterization of the cassava residue**

In order to properly characterize the aerial section of the cassava plant, its agricultural residue, as a possible fuel source for the boilers of the mill, the leaves and stems were ground using a Marconi MA 680 with a 20 mesh filter. The decision to study the residue as a whole was made due to the unrealistic possibility of the separation of the whole plant into its different sections in an actual production environment. The residue used was from a IAC 14 plant, as shown by (VEIGA et al., 2016) to have the best characteristics for the purpose of the biorefinery.

#### **3.1.1 Proximate analysis**

In order to determine the element composition through a proximate analysis of the biomass, the cassava residue was processed in a 2400 CHN Elemental Analyser, where carbon, hydrogen and nitrogen content was determined. Sulphur content was determined through optic plasma spectrometry.

#### **3.1.2 Ultimate analysis**

The analysis was made according to the ASTM E-1755 for biomasses in the Fuel Laboratories of the Department of Thermal and Fluid Mechanics of the Mechanical Engineering College at UNICAMP (ASTM, 1995).

#### **3.1.3 Ash composition**

The ash content of the cassava residue was analysed using the ASTM Norm D-3682 using a SEM/EDS (X-ray spectrometry) electronic microscope (ASTM, a).

#### **3.1.4 Ash fusibility**

Although specific tests can be utilized to identify the proper fusion temperature for the ashes following the norms ASTM E 953 and ASTM D1857, which involve visual recognition of the starting melting point of the ashes (VEIGA et al., 2016) other tests are required in order to completely understand the ash fusion mechanisms that occur during the combustion of the

cassava plant residue. The ASTM E 953 Standard for RDF Ash Fusibility will also be used to further characterize and study the effects of temperature on the ashes fusion temperature (ASTM, b);(??, ??).

### 3.1.5 High heating value

This analysis was made using an IKA C-200 Calorimetric Adiabatic Pump. The ASTM D-2015 Standard Test Method for Gross Calorific Value of Coal and Coke by the Adiabatic Bomb Calorimeter was utilized as norm. This standard was retired in the year 2000 yet remains a valuable asset for the assessment of a biomass's HHV (ASTM, 1996).

### 3.1.6 Low heating value

LHV is not measured instrumentally but by analytical formulas. Equation 3.2, estimated by Bizzo(2003), gives the resulting LHV in dry base:

$$LHV = HHV + 2440 * (9H + U) \quad (3.1)$$

Where:

- HHV - High Heating Value ( $\frac{kJ}{kg}$ )
- LHV - Low Heating Value ( $\frac{kJ}{kg}$ )
- H - Hydrogen content of the fuel ( $\frac{kg}{kg}$ )
- U - Humidity content of the fuel (db)

### 3.1.7 Thermogravimetric analysis in inert and oxidizing atmospheres

The TGA and its resulting derivative (DTG) where done using a Netzsch STA Model 449-F3 Jupiter, from the Fuel Laboratories of the Department of Thermal and Fluid Mechanics of the Mechanical Engineering College at UNICAMP. In this analysis, approximately 30 mg of the residues from the cassava plantation where heated from room temperature to 1000 °C at a rate of 10 °C/min. One test was made using synthetic air for the oxidizing atmosphere and another using argon for the inert.



### 3.2 Energy and mass: inside the cassava mill

The elaboration of a complete mass and energy balance for a cassava mill that does not exist as a whole was only made possible through the gathering of information from various sources, that allowed the junction of the different sectors of the biorefinery into one complete mass and energy flow map. Informations gathered by (CAMACHO, 2009), (LEONEL; CEREDA, 1999), (VEIGA, 2012), (CAMARGO et al., 1990) and (OLSEN, 1995) allowed for the complete mapping of the innings and outings of the cassava ethanol production while (CEREDA, 1994), (CEREDA, 1996) and (LEBOURG et al., 1996) allowed for the mass flows of the starch sector of the biorefinery. All equipments and their nominal electrical consumptions, where gathered from the EBS equipment factory. Figures 4.5, 4.6 and 4.7 show the complete flow map, built from the gathered information. The mass and energy flows where calculated for the processing of 1 ton of fresh cassava root. However, it is necessary to state that in order to reasonably utilize some of the components, especially of the co-generation plant, the entire biorefinery must have the same processing capacity of a medium scale plant so as to justify the cost of certain components.

#### 3.2.1 Available fuel and energy: co-generation of the biorefinery

According to Veiga, the IAC 14 cassava variety presents at harvest 12 months after initial planting a medium production of 30.12 t/ha of roots (w.b.) and a production of 451 kg of field residue per ton of fresh root at 30% humidity. Totalling an average residue production of 13.58 t/ha. This residue is a mixture of the leaves, superior branches and stems. Approximately 20% of the stems are collected and used in order to replant the crop for the next harvest.

In order to generate the energy, the biorefinery must have a co-generation sector that would follow the same schematics as those shown in Figure 3.1. The basic parameters for the turbo generator are the following:

- Intake steam temperature at 460 °C.
- Intake steam pressure at 45 bar(abs).
- Extraction at 8 bar(abs) for flash dryer.
- Expansion from 8 bar to 2.5 bar(abs) for distillation and starch gelatinization.
- Turbine iso-entropic efficiency at 85%.
- Electric generator efficiency at 98%.
- Condensation at 0.27 bar(abs).

For the steam generator the basic parameters are:

- Steam generator efficiency at 85%.

For the industrial processing sector the basic parameters are:

- Cassava root intake rate is,  $\dot{m}_r = 200$  t/hr.
- Initial mass flows are 50% Ethanol and 50% Starch Powder.

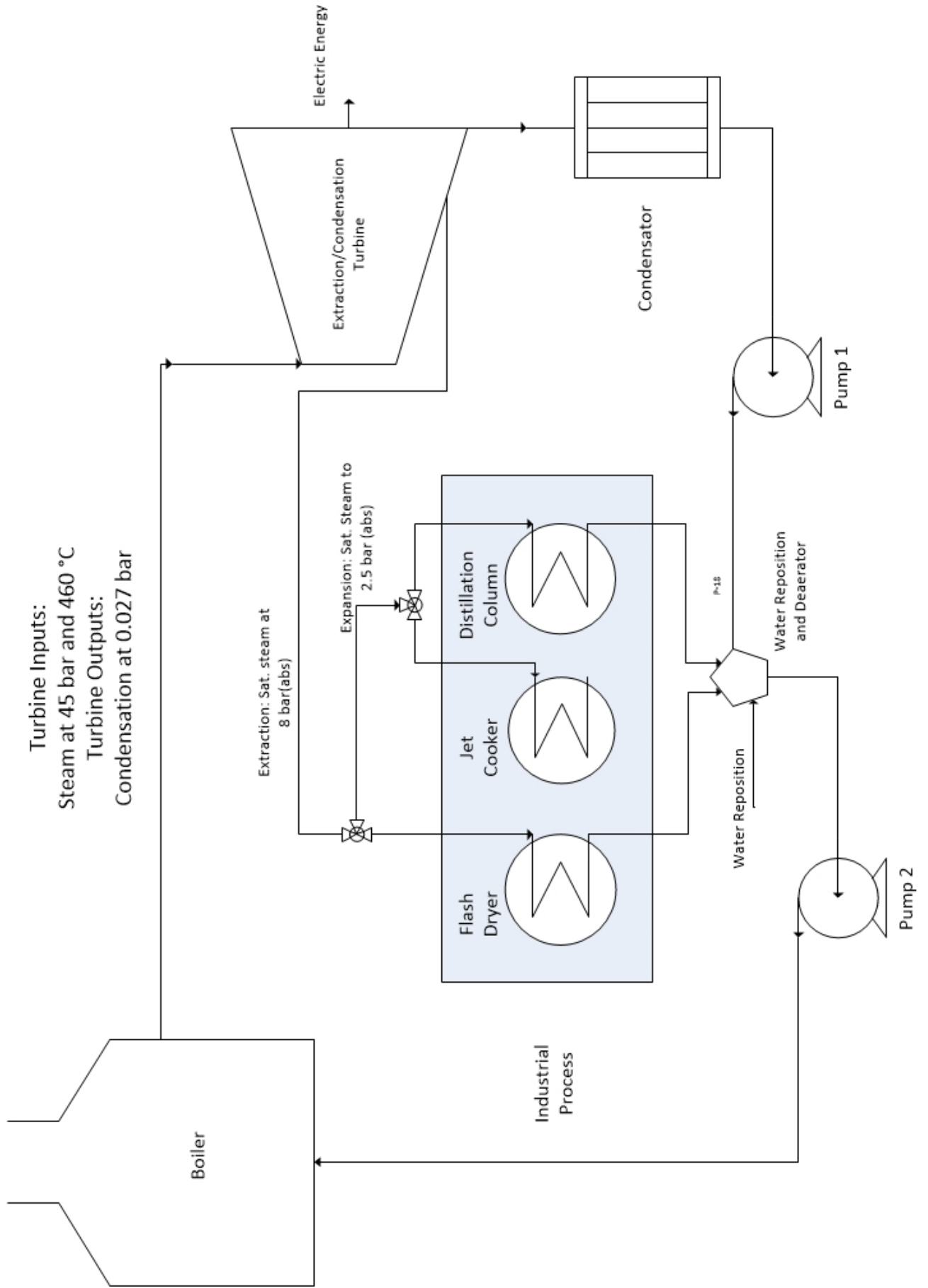


Figure 3.1: Cogeneration scheme

All of these parameters were considered as average for modern cogeneration plants that utilized sugar cane bagasse as fuel sources, this was done as there are no real cogeneration plants that use cassava agricultural residue. The lower temperature was chosen due to the theoretical low ash fusion temperature of the mixed cassava residues as stated by (VEIGA et al., 2016) and the input pressure was determined for a vapor quality of 92% (CARVALHO, 2015) as in figure 3.2 that would guarantee a safe operation for a turbine without steam reheating. Also, all pumps considered for the co-generation sector have an iso-entropic efficiency of 80%.

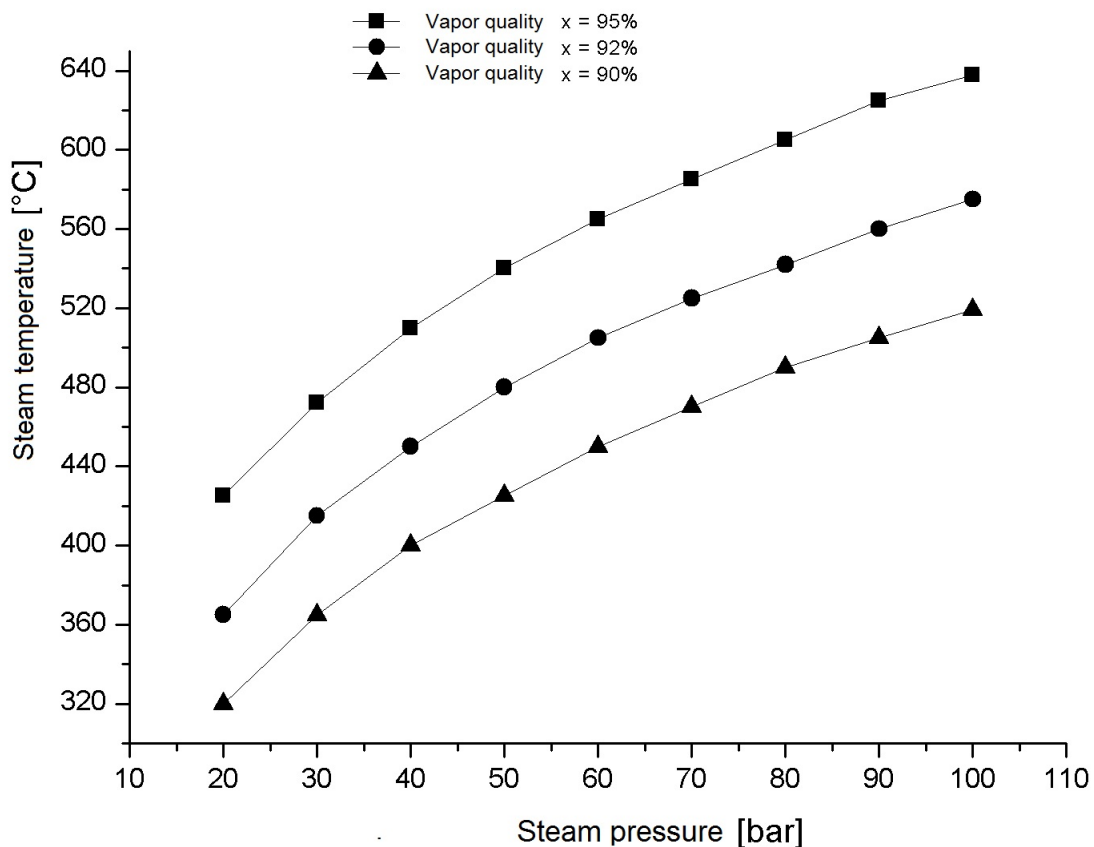


Figure 3.2: Vapor quality curves  
SOURCE: Translated from (CARVALHO, 2015)

The processing input was chosen to be the base parameter for the calculation of all of the other mass flow rates in the other two sectors of the plant. The available fuel to the plant is based on the residue/roots ratios found for the IAC 14 Cassava plant multiplied by the root intake capacity. So, setting this parameter along with the technical specifications of the remaining industrial components, both of the agro-industrial sectors and the co-generation sector, a fuel addition rate or  $\dot{m}_f$ , for the steam generator can be calculated. Using the residues LHV and the generators efficiency.

Finally, the thermal energy necessary to process the roots can now be calculated using both the root intake rate and the steam conditions of each of the 3 thermal processes. This

energy/mass balance will be necessary in order to extract the necessary amount of steam from the turbine. The electricity required for the industrial plant will only vary according to the root intake rate and will subtract from the net electric generation of the bio-refinery.

### 3.2.2 Pre-treatment of roots

The pre-treatment of the roots is a stage in the industrial process is one that is shared by both the ethanol and the starch sectors of the plant and utilizes about a quarter of the total electricity required by the plant at a 50/50 production rate (50% of starch milk is transformed into ethanol and the other 50% to starch).

In table 3.1, the main components of the pre-treatment stage are listed.

Table 3.1: Main Industrial Components of the Pre-treatment  
SOURCE: (EBS, 2017)

Sector	Equipment	Specific Consumption (kWh/T)
Reception/Washing	Un-loader	1.23
	Screw Conveyor	0.49
	Screw Feeder	0.49
	Root Washer	0.49
	RotoPump	0.74
Grinding	Knife Grinder	0.74
	Root Desintegrator	14.8
	Helicoidal Pump	0.49
Extraction	Stainless Steel Roto-Pump	0.74
	Rotating Seivers GL-1200	7.89
	Medium SS Roto-Pump	0.74
Concentration	Large SS Roto-Pump	1.23
	Primary Centrifuge EBS CT-100	4.96
	Medium SS Roto-Pump	0.74

### 3.2.3 Energy needs for starch hydrolysis and saccharification

Turning starch into fermentable sugars is a section of the ethanol sector that requires a minuscule part of the total electric consumption of the biorefinery. The main components of this section are listed in Table 3.2 which also includes the jet cooker, that only consumes thermal energy. Figure 3.3, demonstrates the mass flows within the jet cooker.

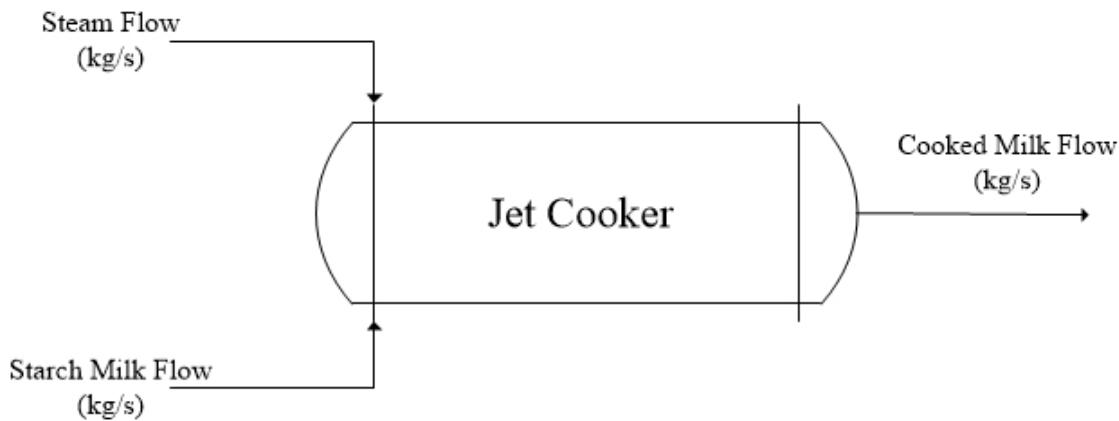


Figure 3.3: Flow diagram for the Jet Cooker.

The complete equation that calculates the steam flow rate for the jet cooker and subsequently the thermal energy required by the process is as follows:

$$\dot{m}_{s1} = \frac{\dot{m}_{milk} C_p \Delta T}{(h_2 - h_1)} \quad (3.2)$$

in which:

- $\dot{m}_{s1}$  is the steam flow of the jet cooker.
- $\dot{m}_{milk}$  is the milk flow rate through the jet cooker.
- $C_p$  is the milk's specific heat in kJ/(kgK).
- $\Delta T$  is the change in the milk flow temperature in °C.
- $(h_2 - h_1)$  is the enthalpy difference between the exit and entry enthalpies of the steam.

Both the jet cooker and distillation column consume steam at 127.5 °C and 2.5 bar(abs). However, the jet cooker injects steam directly into the starch milk flow while the distillation is done through indirect heating. In any case, the steam intake for the jet cooker,  $\dot{m}_{s1}$  in (kg/s) depends solely on the calculated flow of starch milk,  $\dot{m}_{milk}$  in (kg/s) and the milk's specific heat which was calculated proportionally from both water and starch  $C_p$ 's.

Table 3.2: Main Industrial Components of the Saccharification  
SOURCE: (EBS, 2017)

Sector	Equipment	Specific Consumption (kWh/T)
Cooking and Gelatinization	Homogenization Tank	0.49
	Helicoidal Pump	1.27
	Jet Cooker	0
	Hydrolysis Tank	0.49
	Shell-Tube Heat Exchanger	0
Saccharification	Saccharification Tanks	1.23
	Centrifugal Pump	0.74

However, in order to complete the mass and energy balance of the biorefinery, other factors must be taken into account. The stoichiometric conversion factor of the starch hydrolysis and subsequent saccharification as well as recorded efficiencies were gathered from the literature and listed in Table 3.3.

Table 3.3: Starch to glucose conversion factors

	Source	Factor	Unit
Stoichometric Conversion Factor	(SERRA et al., 1978)	1.3071	$\frac{kg_{glucose}}{kg_{starch}}$
Efficiency of the Starch Hydrolysis	(LEONEL; CEREDA, 1999)	0.9	$\frac{kg_{produced}}{kg_{stoichiometric}}$

### 3.2.4 Fermentation and distillation of ethanol

The fermenting process of discontinuous batch fermentation is approximately 13.7% of the total electricity requirements. Table 3.4 shows that this consumption is mainly due to the pumps that transport the wort and fermented wine in and out of the dorns respectfully.

After the wine is filtered, it needs to be pumped through the distillation column and both the hydrated ethanol (97.5 °GL) and vinasse that exit from the distillation process must be taken to their respective storage tanks. The basic components of the distillation sector are also listed in Table 3.4, which also includes the column that only requires a source of thermal energy, as stated before, a flow of steam ( $\dot{m}_{s3}$ ).

Calculating the steam flow required by a distillation column is a bit trickier. The steam flow varies accordingly to changes in the column's internal architecture, wine flows and it's composition. Since the design of a distillation column is somewhat out of place of this dissertation's scope, the steam flow rate for the distillation column,  $\dot{m}_{s3}$  in (kg/s), was set at an industry average for mid-large scale ethanol refineries of 2.2 kg/L of ethanol and converted to

kg/s (BARBOSA et al., 2008). This steam addition rate (low end of average consumption rates) was chosen as the initial concentration factor of the ethanol in the wine before the distillation was greater than an average sugar cane mill's. Mainly, the more ethanol is initially within the wine, the less steam is needed to extract it.

Table 3.4: Main industrial components of the fermentation and distillation  
SOURCE: (EBS, 2017)

Sector	Equipment	Specific Consumption (kWh/T)
Fermentation	Fermentation Dorns	7.4
	Cooling Tank	1.97
	Roto-Pump	2.96
Distillation	Distillation and Rectification Column	0
	Refrigeration Tower	2.96
	Vinasse Roto-Pump	0.99
	Ethanol Roto-Pump	0.99
	RotoPump	0.74

Just like the hydrolysis sector, the fermentation and subsequent distillation of the ethanol needs to include a certain set of conversion factors that again were gathered from the corresponding literature. These are listed in table 3.5 and are necessary to fully construct the mass flows figures in the next chapter.

Table 3.5: Ethanol conversion and distillation factors  
SOURCE: (CAMARGO et al., 1990)

	Factor	Unit
Stoichometric Fermentation Factor	0.6471	$\frac{L_{ethanol}}{kg_{glucose}}$
Efficiency of the Fermentation	0.891	$\frac{L_{produced}}{L_{stoichiometric}}$
Efficiency of the Distillation	0.9663	$\frac{L_{produced}}{L_{stoichiometric}}$

It is important to note that the conversion and distillation factors that were utilized in the calculations of ethanol production are for sugar cane ethanol, as no published cassava ethanol conversion factors were found.



### 3.2.5 Purification and drying of starch

Table 3.6 lists the main remaining components of the production of starch. Here as stated before, the starch milk is purified, concentrated and dried in order to produce a high quality industrial or food-grade starch.

Unlike the previous components that used heat in their processes, the negative pressure dryer also consumes a copious amount of electricity as it needs to circulate air within the dryer in order to decrease the moisture of the starch paste that enters to a final 12-13% humidity.

Table 3.6: Main industrial components of the starch production  
SOURCE: (EBS, 2017)

Sector	Equipment	Specific Consumption (kWh/t)
Concentration	Stainless Steel Roto-Pump	0.37
	Hydro-cyclones	5.43
Dehydration	Centrifuge Dehydrator DC-5000	5.3
Milling	Starch Flash Dryer	9.87

For the flash-dryer needed to dry the starch paste onto 12% humidity, the extraction steam is required to be at 170.4 °C, which has a pressure of 8 bar(abs) at saturation point. Knowing this and knowing the specific heat of solid starch and the starch flow rate,  $\dot{m}_p$  in (kg/s), the needed air flow,  $\dot{m}_{a1}$  in (kg/s), can be found. Sequentially, the intake steam flow rate for the starch dryer,  $\dot{m}_{s2}$  in (kg/s) that will heat the dry air that comes in contact with the starch can be calculated.

Thermally speaking, the calculation of the required steam is not as straight forward as the equation for the jet cooker. The many mass inputs and outputs can be seen in figure 3.4.

Some assumptions about temperatures, air humidity and heat exchanger efficiencies will have to be made.

Some of the considerations made were the following:

- The initial temperature of the starch paste is  $T_{p1} = 30$  °C, while the final temperature is  $T_{p2} = 40$  °C.
- The air that will be used as the drying fluid will enter the steam heat exchanger at  $T_{a1} = 30$  °C at 62% humidity and exit at  $T_{a2} = 140$  °C.
- The air exiting the dryer will be fully saturated at  $T_{a3} = 90$  °C.
- Both the heat exchanger and the dryer were considered 100% efficiency, as no energy is lost to the environment.

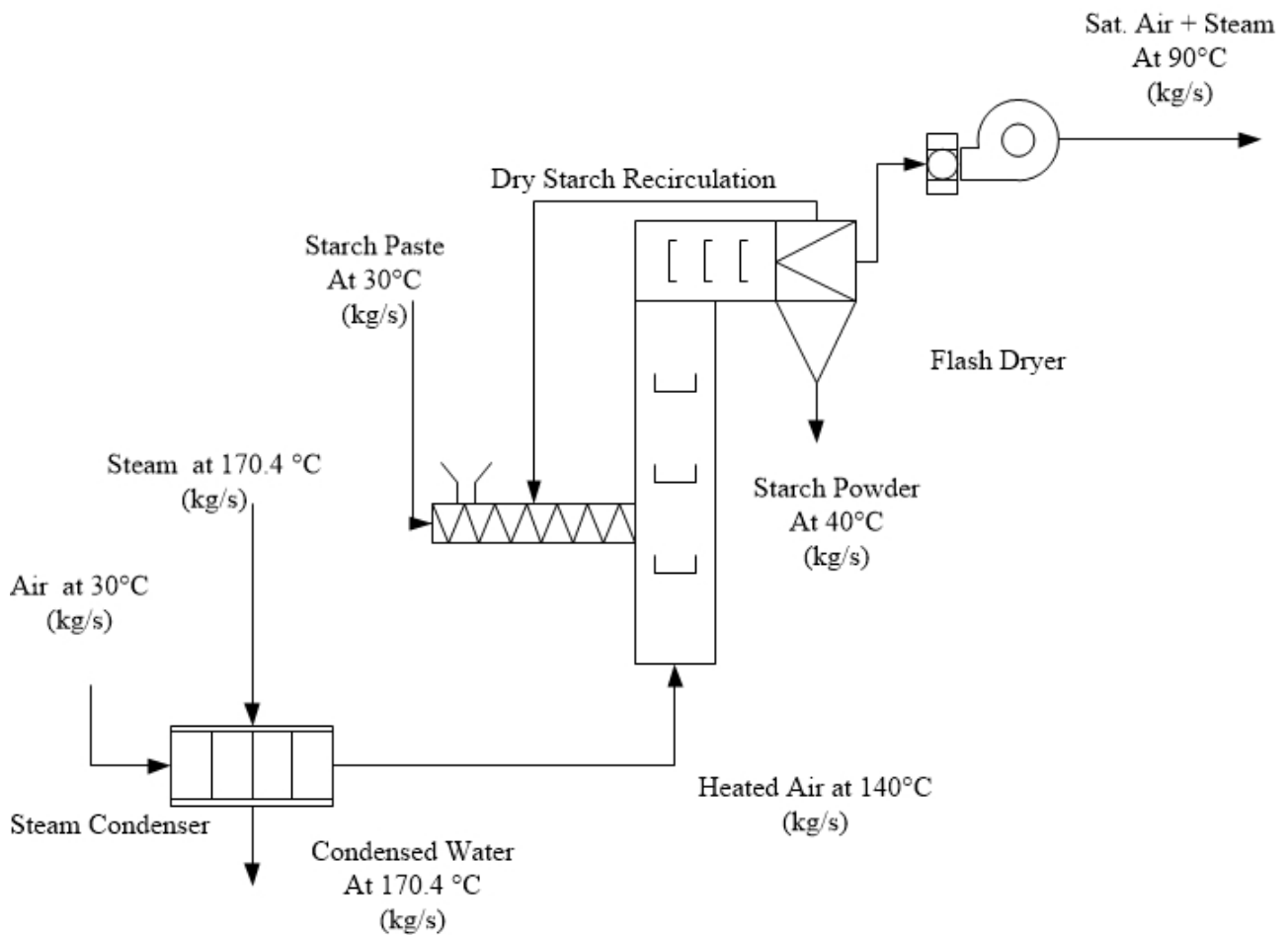


Figure 3.4: Flow diagram for the Starch Dryer.

The following mass and energy equations will characterize the amount of steam flow needed to transform the starch paste into a dry fine powder:

$$\dot{m}_e = (\dot{m}_{p1} - \dot{m}_{p2}) - (\dot{m}_{a1} - \dot{m}_{a2}) \quad (3.3)$$

in which:

- $\dot{m}_e$  is the mass flow evaporated water.
- $\dot{m}_{p1}$  is the mass flow of starch paste.
- $\dot{m}_{p2}$  is the mass flow of starch powder.
- $\dot{m}_{a1}$  is the mass flow humid air.
- $\dot{m}_{a2}$  is the mass flow saturated air.

Here two unknowns exist, the amount of incoming dry air and the amount of evaporated water that is not carried by the saturated air flow.

Next, the energy balance for the dryer will result in the second equation that will create

the solvable equation system for both related variables.

$$\dot{Q}_{a2} + \dot{Q}_{p1} = \dot{Q}_{a3} + \dot{Q}_{p2} + \dot{Q}_e \quad (3.4)$$

in which:

- $\dot{Q}_{a2}$  is the amount of energy carried by the humid air at 140 °C.
- $\dot{Q}_{p1}$  is the amount of energy carried by the starch paste at 30 °C.
- $\dot{Q}_{a3}$  is the amount of energy removed by the saturated air at 90 °C.
- $\dot{Q}_{p2}$  is the amount of energy needed to heat the starch powder to 40 °C.
- $\dot{Q}_e$  is the amount of energy needed to evaporate the remaining amount of water.

Since the energy carried by the drying air and the energy expended to evaporate the starch pastes humidity involve directly their mass flows, with both of these equations it is possible to establish  $\dot{m}_{a1}$ . Finally in order to know the needed steam flow, an energy balance of the steam heat exchanger will be required.

$$\dot{m}_{s2} = \frac{(\dot{m}_a C_{p_{a2}} + \dot{m}_u C_{p_{u2}})T_{a2} - (\dot{m}_a C_{p_{a1}} + \dot{m}_u C_{p_{u1}})T_{a1}}{h_{fv}} \quad (3.5)$$

in which:

- $\dot{m}_{s2}$  is the mass flow of steam in the heat exchanger.
- $\dot{m}_a$  is the mass flow of dry air.
- $\dot{m}_u$  is the mass flow of water vapour at 62% humidity.
- $C_{p_{a2}}$  is the specific heat of air at 140 °C.
- $C_{p_{a1}}$  is the specific heat of air at 30 °C.
- $C_{p_{u2}}$  is the specific heat of water vapour at 140 °C.
- $C_{p_{u1}}$  is the specific heat of water vapour at 30 °C.
- $h_{fv}$  is the evaporation enthalpy of steam at 150 °C.

Finally,  $\dot{m}_s$  is known.



## 4 Results and Analysis

### 4.1 Characterization Results

The material used for the characterization of the agricultural residue of the cassava plant was a sample of the coarsely ground complete upper section of an IAC 14 cassava plant, harvested at 12 months.

#### 4.1.1 Proximate and ultimate analysis

The sample presented an equilibrium humidity of 12.37% in wet base (w.b.) as presented in Table 4.1 for the proximate analysis. This result varied significantly from the results gathered by (VEIGA et al., 2016) and are more closely related to the results obtained by (PATIYA, 2011). The sample also presented a lesser content of volatile matter. This is possibly

Table 4.1: Proximate analysis in mass percentage (%)

Biomass	Source	Humidity (w.b.)	Fixed Carbon (d.b.)	Volatile Matter (d.b.)	Ash (d.b.)
Sugar Cane Bagasse	(JENKINS et al., 1998)	-	11.95	85.61	2.44
Cassava Plant Residue	(VEIGA et al., 2016) Author	9.62 12.37	11.09 21.02	86.03 75.99	2.88 2.99

explained by the degradation of the biomass from prolonged storage. In turn, this decrease in volatile matter resulted in a greater mass percentage of fixed carbon (d.b.) when compared to the two other authors in Table 4.1. Ash content remained closely related to that reported by Veiga.

In the ultimate analysis, the results for the contents of carbon, hydrogen, oxygen, nitrogen, sulphur and chlorine of the IAC 14 plant present results similar to those of soft woods and sugar cane bagasse (JENKINS et al., 1998), when compared to the results found in 2.6. Table 4.2, presents the results gathered and compares them with the results gathered by (VEIGA et al., 2016) in the case of cassava plant residue and (JENKINS et al., 1998) in the case of sugar cane bagasse. With respect to the sulphur and chlorine contents of the biomass, the sample

Table 4.2: Ultimate analysis in mass percentage (%)

Biomass	Source	Carbon	Hydrogen	Oxygen	Nitrogen	Sulphur	Chlorine
Sugar Cane Bagasse	(JENKINS et al., 1998)	48.64	5.87	42.82	0.16	0.04	0.03
Cassava Plant Residue	(VEIGA et al., 2016) Author	42.84 41.29	6.25 6.73	47.21 50.48	0.79 0.66	<0.2 0.50	<0.3 70.34

presents similar results to those measured previously. When compared to average coal samples

in which these two components are of greater relevance due to their aggravation of the high temperature corrosion effects discussed in section 2.6.4, show that there is in a sense little to worry about these components and their interactions in the possible ash conglomerates. These results alongside the ash content and fusion temperature analysis will provide more information on ash deposits on boiler surfaces that can cause a loss of heat exchange efficiency and material corrosion through chemical reactions and mechanical wear and tear, and the according maintenance schedule required for the proper operation of the boiler unit.

#### 4.1.2 Ash composition and fusibility

A sample of the ashes of IAC 14 cassava plant areal section was characterized using a scanning electron microscope in order to measure the various elements present in the ash and their abundance within the sample. As the x-rays emitted from the sample were characterized using the microscope's spectrometer, a list of oxidized compounds within the ash was taken and presented in Table 4.3 with the oxides in mass percentage. The analysis presented an incredibly high content of potassium oxide (approximately 52%) which along side other alkali oxides (phosphorous pentoxide, calcium oxide and manganese oxide) represent an 88.45% of the total ash content. Though these results vary greatly from those found by (VEIGA et al., 2016), as can

Table 4.3: Comparison of ash composition between biomasses

	Sugar Cane Bagasse	Cassava Plant Residue	
	(JENKINS et al., 1998)	(VEIGA et al., 2016)	Author
SiO <sub>2</sub>	46.61	3.44	0.76
Al <sub>2</sub> O <sub>3</sub>	18.99	2.40	-
TiO <sub>2</sub>	2.63	0.14	-
Fe <sub>2</sub> O <sub>3</sub>	14.14	1.32	0.82
CaO	4.47	21.76	12.05
MgO	3.33	13.77	15.02
Na <sub>2</sub> O	0.79	0.28	0.84
K <sub>2</sub> O	0.02	26.43	52.23
SO <sub>3</sub>	2.08	3.54	4.17
P <sub>2</sub> O <sub>5</sub>	2.72	25.43	11.4
MnO <sub>2</sub>	-	0.22	0.56
ClO <sub>2</sub>	-	0.69	2.14
CuO	-	0.28	-

be seen in Table 4.3, Veiga had already stated a possible problem of ash conglomeration due to an alkali index greater than 0.34 kg/GJ (Table 4.4). Veiga's measured alkali index of 0.46 kg/GJ are almost half of those presented in Table 4.4. The 0.82 kg/GJ index found in the sample would mean that the effects of ash fouling would most definitely have a great impact on the operation and maintenance of the furnace while burning the cassava residue. The index was sharply driven

up by the greater quantities of potassium oxide within the ash. However, as the alkali index is not a definitive standard for biomasses other tests would be required to fully understand if the great ash conglomeration hypothesized by the index's standards would indeed be applicable for the IAC 14 ash deposits.

Table 4.4: Alkali index of various biomasses in kg/GJ

	Sugar Cane Bagasse (JENKINS et al., 1998)	Cassava Plant Residue (VEIGA et al., 2016)	Author
AI	0.06	0.46	0.82

In order to further understand the ash fusion process, the ash samples were subjected to an analysis according to the Ash Fusibility Test (ASTM E-953) that sets the various stages of ash deformation at their proper temperatures. As it can be both in Figure 4.1 and Table 4.5, the ash cones begin to present visual changes in their cone shape at 1250 °C.

Figure 4.1: Example of ash fusion imaging

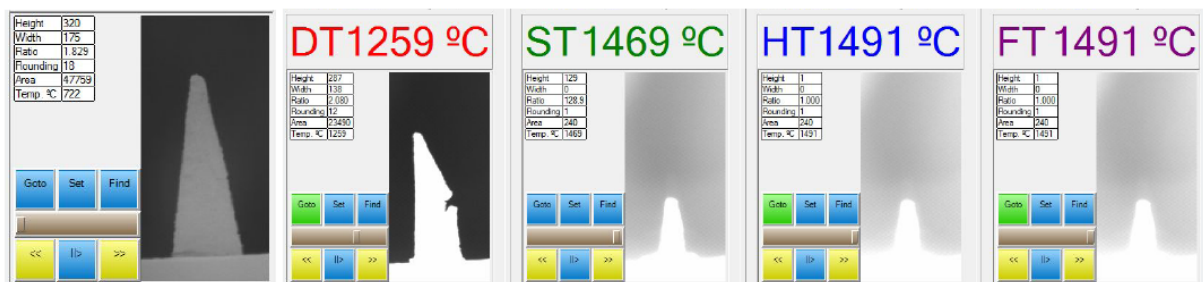


Table 4.5, presents the four different categories for the test in which:

- DT - Initial deformation temperature.
- ST - Softening temperature.
- HT - Hemispherical temperature.
- FT - Fluid temperature.

Table 4.5: Fusion temperature for cassava residue ash in oxidative atmosphere

Method	DT(°C)	ST(°C)	HT(°C)	FT(°C)
Oxidative Atmosphere	1228	1483	>1500	>1500
	1246	1487	>1500	>1500
	1243	>1500	>1500	>1500
	1259	1469	>1500	>1500
	1255	>1500	>1500	>1500
	1258	>1500	>1500	>1500
Average	1248	1480	>1500	>1500

In any sense, the temperatures gathered in Table 4.5 present different ramifications for the ash deposit problem than the alkali index, as the initial deformation temperature is relatively high at 1248°C and the complete fusion temperature or FT, is >1500°C, which signals that there is little to worry about the ash becoming fluidized and depositing on the heat exchanging parts of the functioning boiler at 460°C. In essence, the ash deposits from the IAC 14 cassava plant, would probably have a considerate amount of ash fouling according to the Alkali Index and little if any at all slagging according to the results of the E-953 Test.

#### 4.1.3 High and low heating values

The values for high heating value obtained through the use of a calorimeter are given in Table 4.6. These results are somewhat higher than those found in (VEIGA et al., 2016). It seems to be that the reason for this is that the previous results were measured for the different areas of the plant (stems and branches) and the results were presented as an average of the values. However, the amount of biomass of each part of the plant varies in the percentage of total biomass available therefore, an average of the heating values of the different sectors would not give an accurate result. IN the present test, the plant was ground as a whole in order to prepare the test samples.

Table 4.6: High and low heating values (30% humidity) for cassava residue.

SOURCE	HHV (MJ/kg)	LHV (MJ/kg)
(VEIGA et al., 2016)	17.21	15.01
Author	18.90	16.68

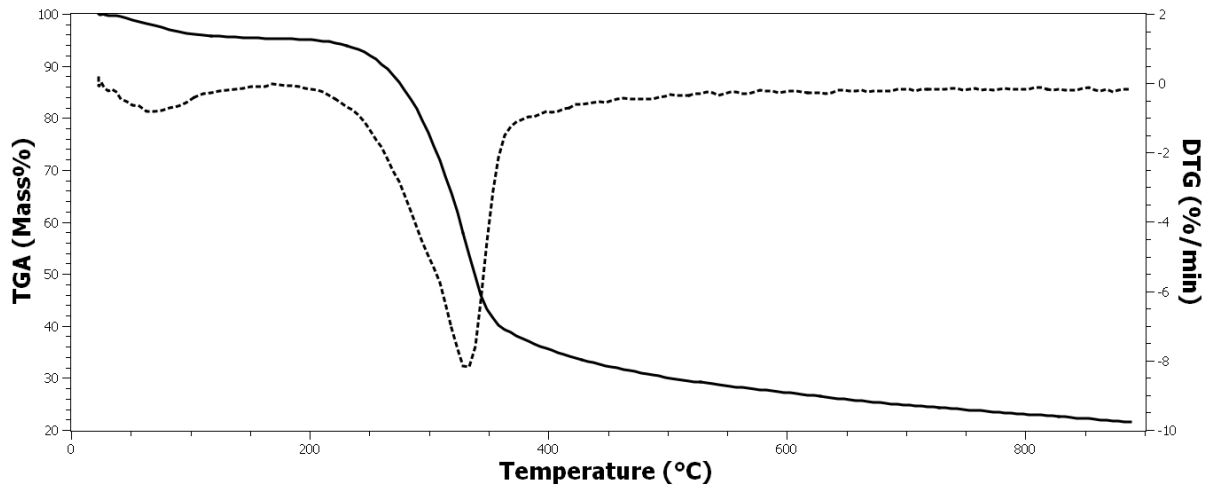
In any sense, the sample does present HHV values similar to other woody non-oily biomasses, including sugar cane bagasse. The considered humidity of 30% for the calculation of the low heating value of the biomass was also presented by Veiga and was accepted for the current sample. The LHV of 16.68 MJ/kg gathered, would mean that the IAC 14 presents a reasonable energy value for its combustion at its considered equilibrium humidity.

#### 4.1.4 Thermo-gravimetric analysis

The thermo-gravimetric analysis of both the IAC 14 sample and of its ashes are presented in Figures 4.2 and 4.3. With the initial dip in the DTG curve of figure 4.2 between 0 and 100°C being the initial removal of equilibrium humidity and the even greater dip in the DTG curve between 250 and 400°C representing the volatilization of the biomass during the mid stages of pyrolysis in the inert atmosphere.



Figure 4.2: TGA/DTG curves in inert atmosphere of a sample of IAC 14 cassava.



In the case of the ash residue in the TGA/DTG curves of Figure 4.3, the curves present a set of various sudden accelerations of the rate of ash degradation suggesting that some compounds within the ash volatilize at greater temperatures. However, as there is a large drop in mass percentage (100-80%), the test suggests that there is a significant amount of ashes that can vaporize and create agglomerations of deposits elsewhere in the boiler.

Figure 4.3: TGA/DTG curves in oxidative atmosphere of ash from the IAC 14 cassava plant.

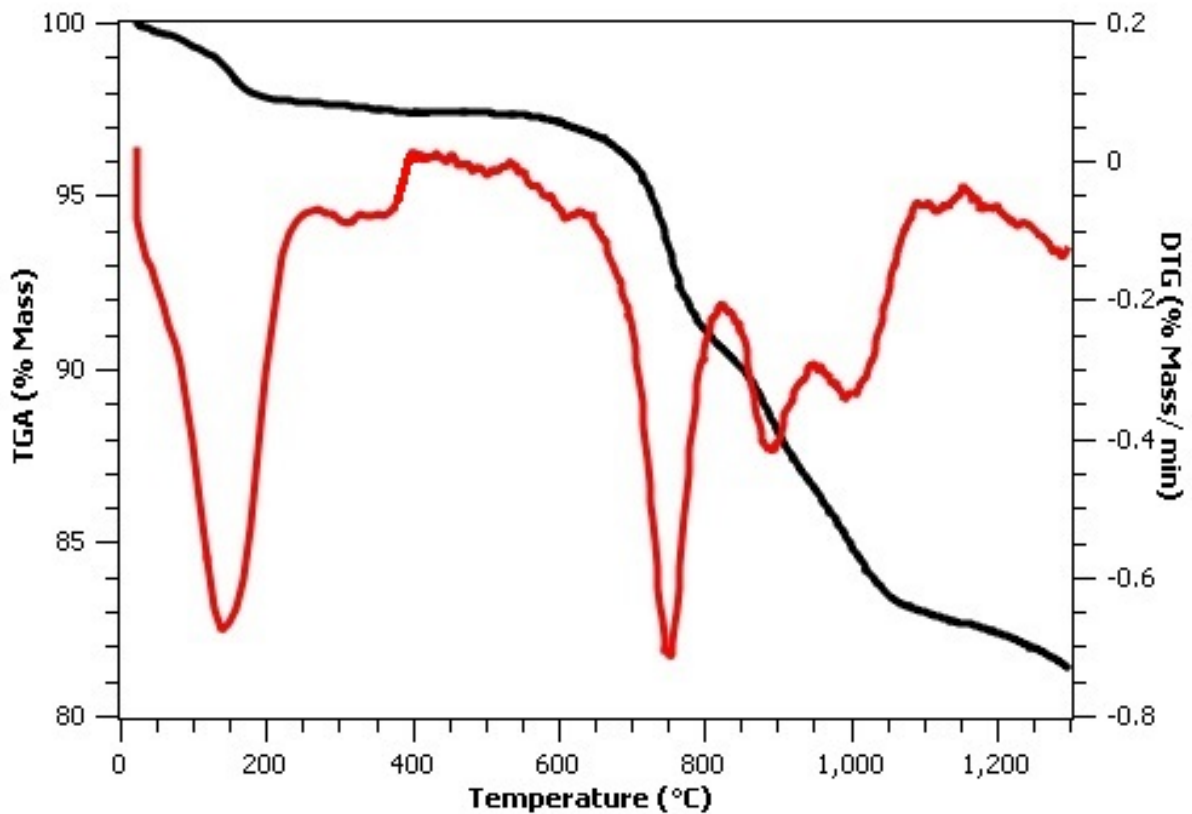
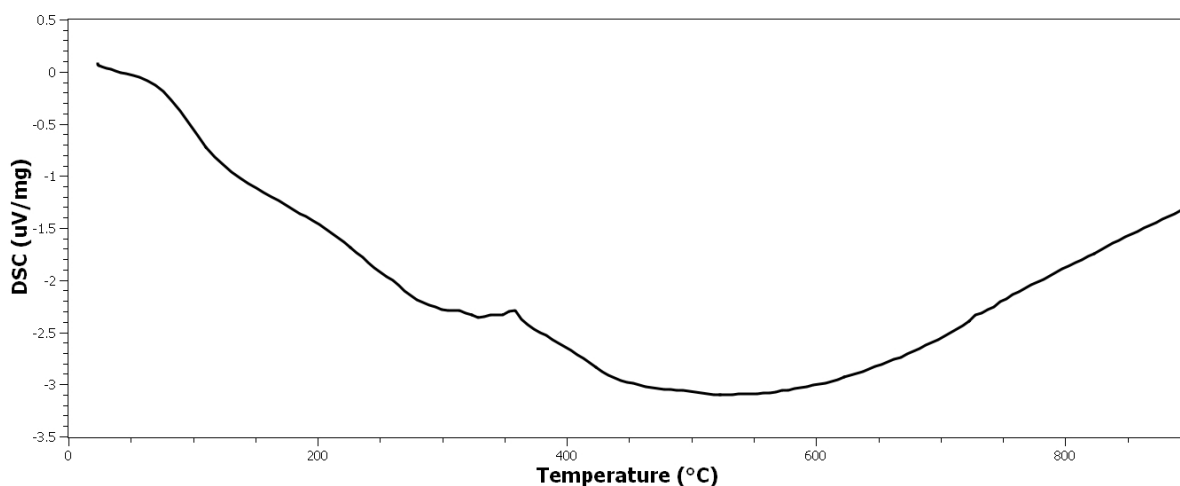


Figure 4.4 contains the curve that describes the rate of energy emission during the degradation of the ash deposits suggests some exothermic process occurring between 200-400 °C (ash fusion perhaps; although not a great percentage according to the TGA curve of Figure 4.3). A set of exothermic process occur during the entire test, with a large endothermic process occurring before the final temperature of 1300°C that suggest some sort of vaporization of the ash components.

Figure 4.4: DSC curve in an inert atmosphere the IAC 14 cassava plant.



## 4.2 The industrial processing sector

As stated in section 3.2.1, the set intake processing capacities for the biorefinery are 200 t/hr of fresh roots. These processing capacities were divided into 5 different scenarios for final product output, which varied for the amount of concentrated starch milk, exiting from the pre-treatment area of the processing plant onto the two final product lines; ethanol or starch powder. Table 4.7 displays the different production scenarios, in which 50% of the concentrated milk is used for the production of bio-ethanol and the remaining 50% of starch milk is directed to the production of starch powder as in case 1.

Table 4.7: Production scenarios studied.

Case	Final Product Line Input
1	50% for Ethanol and 50% for Starch Powder
2	75% for Ethanol and 25% for Starch Powder
3	25% for Ethanol and 75% for Starch Powder
4	100% for Ethanol
5	100% for Starch Powder

But not only are the final industrial product outputs needed in order to establish the total

outputs of the biorefinery. Table 4.8, references the specific electric consumptions of the areas and sectors within the industrial processing plant. The total consumption of electricity will vary based on the chosen production scenario and will in turn vary the final net power available for sale to third party consumers of electricity.

Table 4.8: Specific electricity consumption of the industrial processing sector.  
SOURCE: (EBS, 2017)

Area	Sector	Specific Consumption (kWh/t) <sup>1</sup>
Pre-treatment	Reception/Washing	5.93
	Grinding	16.57
	Extraction	10.54
	Residue	2.30
Ethanol	Cooking and Liquefaction	2.26
	Saccharification	1.96
	Fermentation	12.26
	Distillation	5.64
	Concentration	11.74
Starch	Dehydration	5.52
	Milling	10.05
	Storage	5
TOTAL		89.79

Necessary for the calculations presented in the previous tables, Figures 4.5, 4.6 and 4.7 are the complete mass flow diagrams for the industrial processing section of the biorefinery. All of the diagrams were built for the processing of approximately 55 kg/s (200t/hr) of fresh cassava roots and represents the mass flows for case 1 (50% ethanol - 50% starch powder).

Figure 4.5 presents the diagram for the biomass pre-treatment sector. Here, as stated before in Section 2.3.1, the roots are cleaned using both fresh water and re-utilized vegetable water flows coming from the different filtration steps of the starch milk processing. All of the flows are given in kg/s and the percentage of DS is the mass content of dry starch particles within the milk. From this area, the mass inputs are 55 kg/s of fresh roots, 60.9 kg/s of fresh water and an input of 25.6 kg/s of starch milk at 7.8% DS coming from the starch powder area. The outputs were calculated to be 218.85 kg/s of vegetable water. This residual water has to be treated in order to be re-inserted into the local water treatment system or used for field irrigation. As stated before, this residue can be anaerobically treated in a bio-reactor in order to produce bio-gas. The pre-treatment process also delivers 33.8 kg/s of dry bran which can be sold as animal feed or mixed with the vegetable water in the reactor for the production of a greater amount of bio-gas. Finally, the most important output of this area is the 57.5 kg/s of concentrated starch

milk at 34.2% DS which will then be directed onto either the ethanol production line or the starch powder line (equally for case 1).

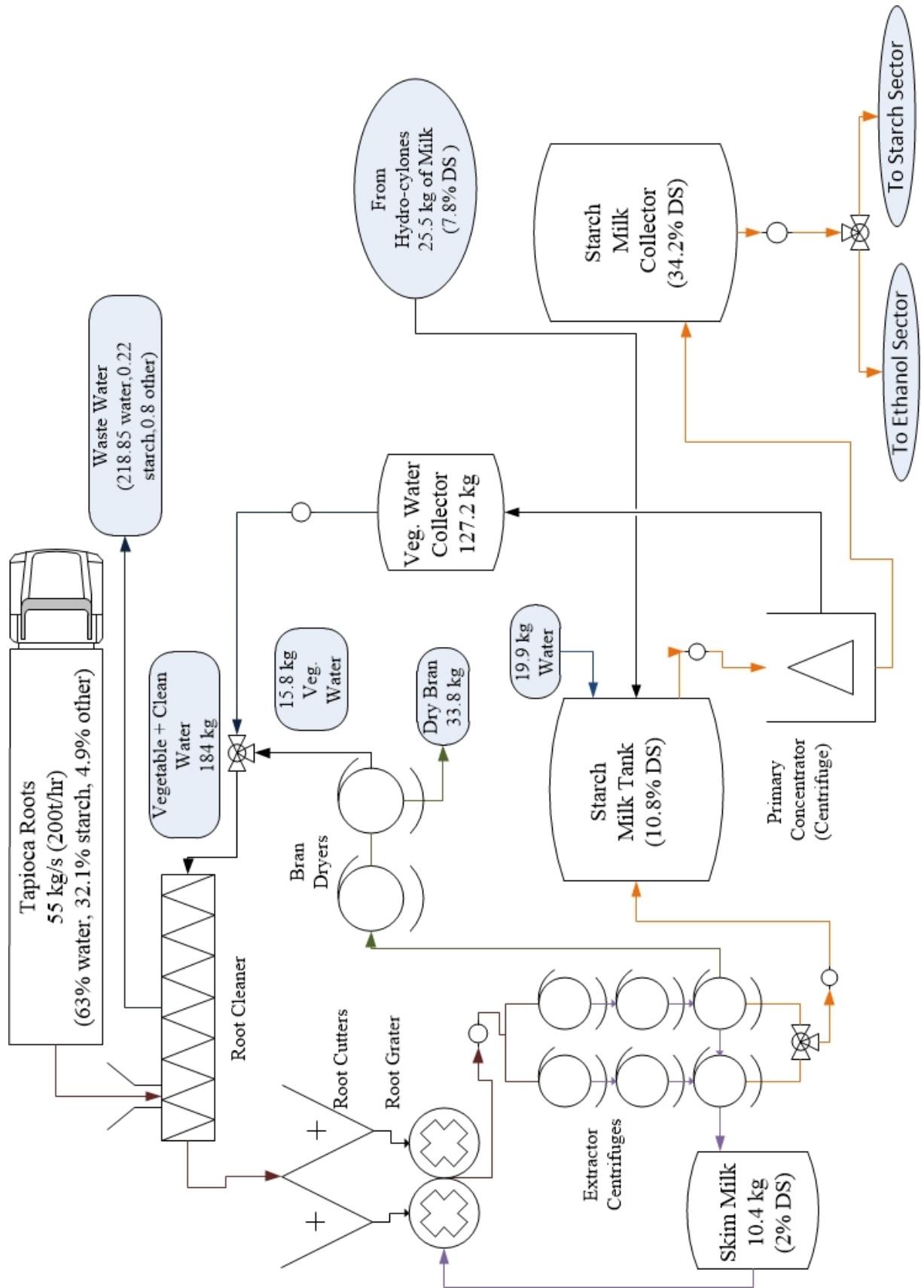


Figure 4.5: Pre-treatment area of the cassava biorefinery.

Figure 4.6, on the other hand describes the mass flow diagram for the starch powder production area. Here, the principal inputs are 28.5 kg/s of concentrated starch milk, incoming from the pre-treatment area. 3.3 kg/s of fresh water are required to assist in the final dehydration of the starch powder in the vacuum dehydrator. A flow of steam at 170.4 °C and 8 bar(abs) of 6.9 kg/s is required in the flash dryer in order to heat a flow of 124.4 kg/s of air from 30 to 140 °C. The stream of saturated water is recuperated from the flash dryer and returned to the boiler feed loop in order to generate more steam. The outputs in this area include the 25.6 kg/s of low concentration milk (7.8% DS) that is sent to the concentrator in Figure 4.5. 4.3 kg/s of humidity removed from the starch powder in the flash dryer leave with the incoming flow of 124.3 kg/s of heated air. Finally, 7.1 kg/s of finished starch powder with a humidity of 13.3% is bagged and shipped to consumers.

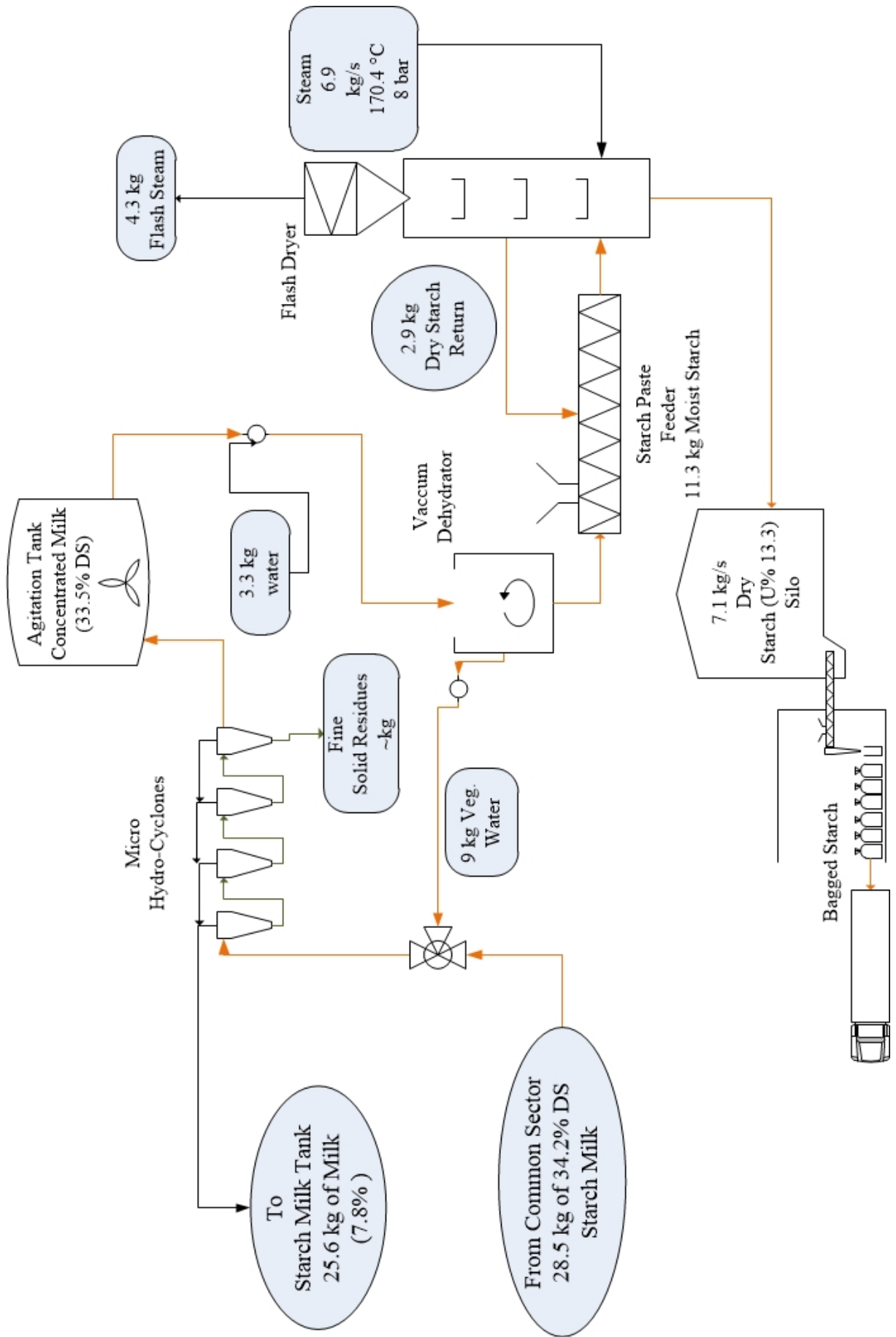


Figure 4.6: Starch production area of the cassava refinery.

Figure 4.7, contains the relatively more complex mass flow diagram for the ethanol production sector. The inputs and outputs for this area are more in comparison to the other 2 areas. The principal input is the 28.5 kg/s of concentrated starch milk from the common pre-treatment sector. Fresh water is added both to decrease the concentration of the starch milk to 30 °Br using 3.9 kg/s of water and the concentration of non-fermentable sugars during the saccharification stage by using 26.2 kg/s of water. In both of these stages, enzymes which enable both the hydrolysis of the starch (6 g/s of  $\alpha$ - amylase) and the saccharification of the dextrans (8g/s of Glucoamylase and Maltogenese). The other inputs are stream flows of saturated steam at 127.4 °C at 2.5 bar(abs) that feed both the jet cooker that enables the initial gelatinization of the starch as the ethanol distillation column. The jet cooker consumes 2.2 kg/s of steam which is directly injected into the starch milk flow. The distillation column however is the most heat consuming process of them all and required a stream of 12.9 kg/s of the saturated steam in order to separate the ethanol from the vinasse. The outputs are 0.3 kg/s of steam removed by the a flash cooler placed after the gelatinization tubes that feed the dextrinization tanks as the enzymes that break down the inflated starch gel onto sugars require a lesser temperature to properly process the starch. 5.6 kg/s of CO<sub>2</sub> exit the fermentation tanks as the sugars are converted into alcohols by the yeast particles. 0.01 kg/s of the wine filter are removed( mainly fibers and yeast) and the distillation column removes 50.7 kg/s of vinasse and other sub-products of the fermentation process. To conclude, the industrial plant produces 5.7 kg/s of hydrated 95.6 °GL bioethanol or 7.2 L/s that will be stored in tanks for transportation to consumers.



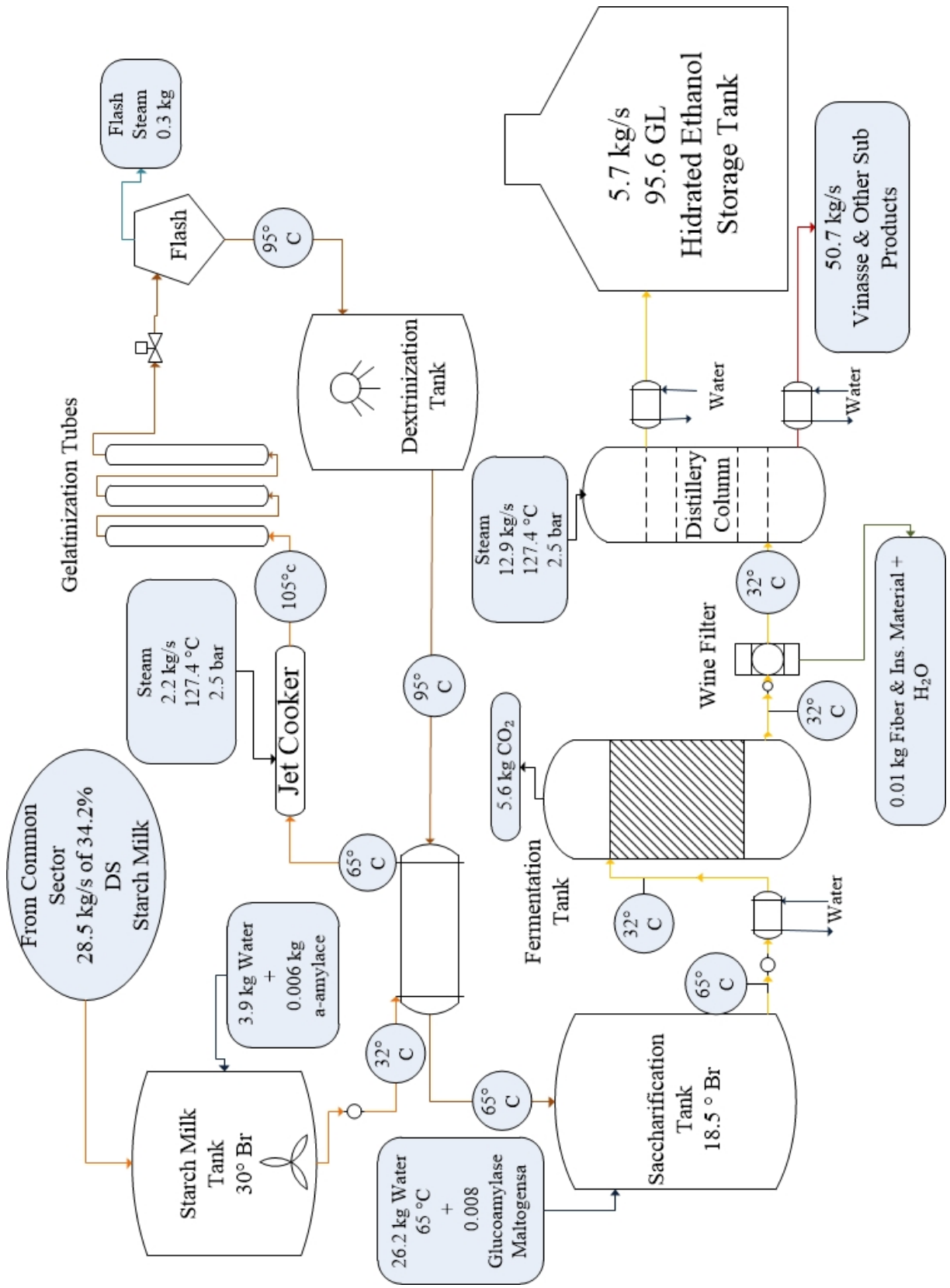


Figure 4.7: Ethanol production area of the cassava refinery.

### 4.2.1 The co-generation sector

To properly calculate the amount of net electricity generated by the biorefinery, the software CYCLE-TEMPO created at Delft Technical University in Holland, was used to construct a model of the co-generation system that would provide both heat and power to the industrial processing sector of the refinery. Figure 4.8, represents the system schematics as constructed utilizing the software's interface. It is a simple steam cycle with the required refrigeration systems (Apparatuses 3,10 and 12), the industrial processing sector (Apparatuses 6,7,10 and 13), boiler, extraction/condensation turbine, generator and required pumps. Table 4.9, presents the complete apparatus list with intake conditions as established in section 3.2.1. The boiler, as the

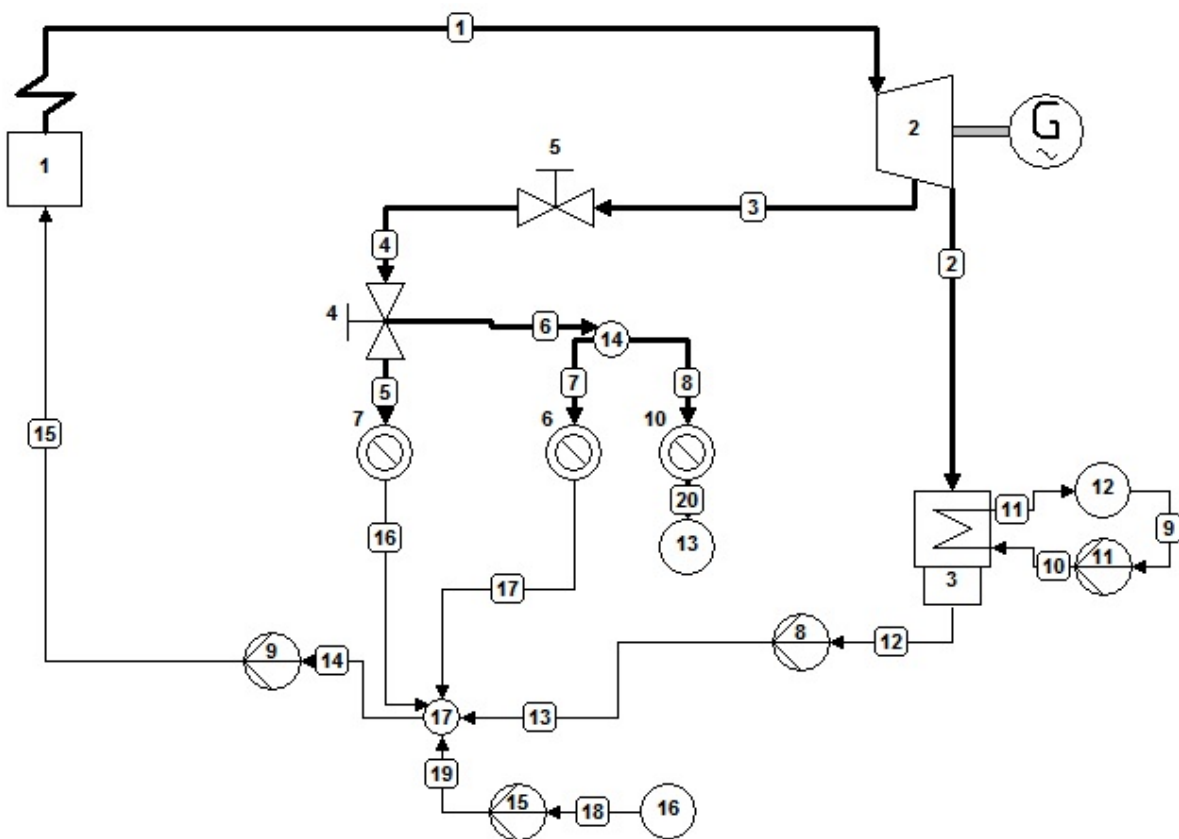


Figure 4.8: Co-generation schematics as constructed on CYCLE-TEMPO software.

principal component, was established as the system constant for the various scenarios. Feed with 100% of the gathered agricultural wastes produced per hectares from the IAC 14 cassava plantations. As shown in Table 2.2.the IAC 14 produced 30.12 t/ha of fresh root (w.b.) and 316 kg/t<sup>2</sup> of dry waste. Considering a humidity of 30% each hectare of cassava produces 451 kg of biomass that will be used as fuel (VEIGA et al., 2016). In other words, for a set root intake of 55 kg/s (200t/hr), there is a fuel input of 25.06 kg/s for the boiler. Since, the biomass presented a 16.68 MJ/kg LHV as presented in Table 4.6, this provides an energy flow of 421.9 MW of

<sup>2</sup>per ton of fresh root

Table 4.9: Equipment identification for Fig.4.8 and intake conditions.

Item	Equipment	$T_{in}$ (C°)	$P_{in}$ (bar abs)
1	Boiler	39.3	45
2	Turbine	460.0	45
3	Condenser	22.34	0.027
4	Extraction Valve	170.4	8
5	Distribution Valve	170.4	8
6	Distillation Column	127.4	2.5
7	Flash Dryer	170.4	8
8	Condensate Pump	22.3	0.027
9	Boiler Intake Pump	39.3	2.5
10	Jet Cooker	127.4	2.5
11	Cooling Pump	20.0	1
12	Refrigeration Water Source	20.0	1
13	Jet Cooker Steam Sink	127.4	2.5
14	Distribution Valve	170.4	8
15	Water Replacement Pump	20.0	1
16	Water Replacement Source	20.0	1
17	Condensate Intake Valve	39.3	2.5

fuel, which for a thermal efficiency of 85% generates approximately 112.3 kg/s of super heated steam at 45 bar(abs) and 460°C. All of this steam is not utilized completely in the extraction/condensation turbine as there is one steam bleed in place for the extraction of process steam that feeds the heating components used in the processing sector of the refinery (jet cooker, distillation column and flash dryer). The amount of steam bled, varies accordingly for each of the 5 cases established in the previous section as the steam requirements for the different lines are not equally divided. These bleeds can range from as little as 13.8 kg/s of saturated steam at 8 bar(abs) for case 5, to as much as 30.2 kg/s for case 4 which produces only ethanol. The extraction line was kept at 8 bar for the purpose of model simplicity. Considering the base case (case 1), 22 kg/s are bled from the turbine in order to produce hydrated ethanol and starch powder.

The same variations are valid for the electric consumption of either production line, although the power usage varies little in comparison to the heat consumption. Case 5 (100% Starch powder) presents the largest electricity consumption of all of the cases at 16.4 MW and case 4 (100% ethanol) is the least power intensive process of them all at 14.1 MW.

As it can be seen, the ethanol line consumes more heat and the starch powder line consumes more power. Table 4.11, presents the heat and power consumptions and outputs for the biorefinery, as well as the efficiencies of the co-generation cycle coupled with the industrial processing demands. Absorbed power by the boiler remains constant for all cases as in all five the boiler is feed with the same amount of biomass (25.06 kg/s).

The auxiliary power consumption includes not only the electric requirements of the in-

Table 4.10: Heat and power for multiple production scenarios in MW.

Case	1	2	3	4	5
Absorbed Power	421.9	421.9	421.9	421.9	421.9
Delivered Gross Power	90.9	89.1	92.8	87.1	94.7
Aux. Power Consumption	15.2	14.6	15.8	14.1	16.4
Delivered Net Power	75.6	74.3	76.9	73.0	78.3
Delivered Heat	48.6	57.4	39.7	62.3	30.8
Total Delivered	124.2	131.7	116.6	139.3	109.1
Efficiencies			-		
Gross	21.5%	21.1%	22.0%	20.6%	22.4%
Net	17.9%	17.6%	18.2%	17.3%	18.5%
Heat	11.5%	13.6%	9.4%	15.7%	7.3%
Total	29.4%	31.2%	27.6%	33.0%	25.81%

dustrial sector, but also the energy used by the various pumps within the co-generation cycle. The delivered heat is the amount of energy in the form of heat, used by the industrial sector. It is interesting to notice that although case 4 presents the largest total energy efficiency, it is by far the worse case for the sale of electricity with a delivered net power of 73.0 MW. Ethanol production consumes the least amount of auxiliary power (14.1 MW), but the sheer amount of steam that is bled from the turbine (30.2 kg/s) places this case within the lowest gross and net power efficiencies.

Table 4.12 presents all three of the final products of the biorefinery. Case 1, or the established base, generates 75.6 MW of surplus power or 272.2 GJ/hr, while producing 26,033 L/hr of hydrated ethanol and 25,500 kg/hr of finished starch powder.

In order to understand the true magnitude of the production values of this biorefinery, Table 4.12 makes a comparison with an average sugar cane biorefinery in the State of São Paulo. With an average production of 68.86 kg of sugar and 42.88 litres of ethanol per ton of processed sugar cane, with a production ratio similar to that of scenario 1, a sugar mill with the same processing capacity of the cassava biorefinery (200 t/hr) would produce far less alcohol and sugar than the equivalent ethanol and starch powder for the cassava biorefinery. The surplus electricity generation with optimal conditions for the moder sugar mills is 200 kWh/t (??, ??) and the agricultural yield of sugar cane stalks is 76.8 t/ha, more than double of that considered for the IAC 14 cassava plant. The solid food stuff yield is greater in sugar production and the same can be told for the average surplus electricity per hectare in sugar mills due to the greater

Table 4.11: Final production scenarios.

Input Capacity	200 tons of fresh root per hour					Unit
	Final Output					
	1	2	3	4	5	
Ethanol	26,033	39,049	13,016	52,066	0	L/hr
	3,931.0	5,896.4	1,965.4	7,862.0	0	L/ha
Starch Powder	25,500	12,750	38,250	0	51,000	kg/hr
	3,850.5	1,925.3	5,775.8	0	7,701.0	kg/ha
Surplus Energy	272,160	257,480	275,040	262,800	281,880	MJ/hr
	41,096	38,880	41,531	39,683	42,564	MJ/ha

agricultural yield of sugar cane plantations. The ethanol production produces a different result however, as the amount of carbohydrates that can be transformed into fermentable sugars is greater in the cassava root than in the sugar cane stalk. In any sense, the cassava biorefinery presents a greater amount of finished product as ton per ton of cassava does contain a greater carbohydrate content against sugar cane, and in the case of surplus energy production, consumes far less electricity than an average sugar mill.

Table 4.12: Comparison with an average sugar mill for the State of São Paulo.

	Cassava Biorefinery	Sugar Mill	
Ethanol	26,033	8,576	L/hr
	3,931.0	3,293.2	L/ha
Starch Powder/Sugar	25,500	13,772	kg/hr
	3,850.5	5,288.4	kg/ha
Surplus Energy	272,160	144,000	MJ/hr
	41,096	55,296	MJ/ha

However, it is important to note that as this processing plant is a proof of concept, there is currently no agricultural and logistical industrial capacities to provide the flow of cassava root required to maintain the processing plant functioning at the 200 t/hr scale. This biorefinery

working for 24 hours, 7 days a week, 365 days a year, would consume require more plantations than the current land planted with cassava in the State of São Paulo with a current plantation of 53,152.8 ha of industrial quality cassava plants and a production of 1,013,571 t of roots. Considering a yield of 30.12 t/ha and a 12 month harvest, the biorefinery would use up 58,013.2 ha and 1,752,000 t of fresh root, requiring an expansion of industrial grade productive land just to supply this biorefinery.

## 5 Conclusion

In conclusion, the concept of a cassava fed biorefinery proved to be plausible from the perspective of mass and energy balances. The 200 t/hr processing plant at scenario 1 (half of input is sent to either ethanol or starch powder production line) produces more final products than an average modern sugar refinery in the State of São Paulo. The biorefinery produces 26,033 L/hr of 95.6 °GL hydrated ethanol and 25,500 kg/hr of finished starch powder of 13.3% humidity. It also has a gross power output of 90.9 MW utilizing a 90.2 t/hr of the IAC 14 agricultural residue. 15.2 MW of power are consumed through the industrial processing and operation of the co-generation system creating a surplus power availability of 75.6 MW. The high amount of surplus electricity, comes from the small internal consumption unlike a sugar cane mill that requires a great deal of both heat and power in order to process the biomass into finished products

The characterization of the residue did present some concerns as to its utilization and possible excess of ash deposition in boiler components but varied results determined that although there is a great deal of alkali components within the ash (almost 85%), they do not necessarily translate into low fusion temperature ashes. These results diminish the previously held concerns of high maintenance costs and low operating time for the boiler. The agricultural residues of the IAC 14 cassava plant present similar characteristics to other agricultural residues much like sugar cane straw and are therefore in need of more thorough testing to understand their behaviour in more life-like situations.

In future works, a pilot combustion chamber could be devised in order to properly understand the mechanics of cassava ash deposits on high temperature boiler components. This information could very well establish that the boiler exit conditions of the super saturated steam at 460 °C and 45 bar(abs) are in fact more conservative than required in order to guarantee the prolonged functioning of the boiler system. With the increase of final steam temperature and pressure even more electricity can be generated guaranteeing a stable source of renewable energy for the years to come.





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