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Subject

Refining Green Plants to Protein Cakes and other useful products in the African Country Zambia

Final Report

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Summary

This design report is the final report of Conceptual Process Design of the plant for the Refining Green Plants to Protein Cakes and other useful products in the African Country Zambia.

Compared to the 3.5 million cows and 600,000 goats, a relatively small amount of pigs (350,000) is found in Zambia. This is mainly caused by the high price of feed components, as they now are imported from e.g. Argentina (310 dollars/ton for Soy cake at a protein concentration of 47%). The aim of this process is to lower the price of protein cakes. If this is achieved, an increase in the number of pigs could be expected. At the same time, we looked for possibilities to produce other useful products, such as electricity and ethanol production. The actual process configuration depends on the location of the process and the type of the product.

The team made four scenarios for the project; two large-scale and two small-scale processes. A small-scale process is chosen for the design, in which enough protein cakes and electricity are produced for a farm with 5,000 pigs. In this scenario, legumes will be cultivated and harvested. The legumes will be separated into fibres and low quality protein cakes, and gasification is applied to make the fibre into electricity. For the scenario with ethanol production only a rough design is made, in order to give an estimate of the feasibility of ethanol production.

The plant is designed with an annual production scale of 2,820 tonnes of protein cakes with at a price of 186 Euro/ton, and 628,000 kWh of electricity. The total investment for this plant is determined to be 8.2 million euros. Annual profit is minus 1.5 million euros, making the process highly unfeasible.

This report is divided into 16 chapters. The introduction chapter provides the conceptual design aspects for this project. Process options and the options chosen are included in chapter 2. The kernel of the design, the so-called Basis of Design, forms chapter 3. Background information, such as feedstock, products, wastes, utilities, plant location, costs etc. are covered in this chapter. The thermodynamic properties, such as the thermodynamic models and thermodynamic data are written in chapter 4. In chapter 5, information on the raw materials is provided, which includes grasslands in Zambia and grass composition. The "back-bone" of the process, such as the process flow schemes (PFS), criteria and selection, process stream summaries and mass and heat balances are covered in chapters 6 and 7.

Process and equipment design and the resulting equipment data sheets are produced in chapter 8. Chapter 9 provides the design of the control system of the plant. Chapter 10 deals with the wastes produced by the plant, while chapter 11 looks into the process safety aspects. Transport and marketing strategy can be found in chapter 12. The future potential for the process in both China and the Netherlands are discussed in chapter 13.

Economic evaluation based on income, investment and operating costs is detailed in chapter 14. Creativity and group process methods are shown in chapter 15, followed by conclusions and recommendations in the final chapter, chapter 16.

Contents

1. Introduction

This report is made within the framework of the course Conceptual Process Design which is part of the Master Degree in Chemical Engineering at the University of Technology in Delft. In consultation with two companies (Shell Global Solutions International B.V. Amsterdam and ATO, IMAG & Agrotechnology and Food Department Wageningen) and the Process System Engineering department at DelftChemTech, the topic is chosen.

The topic for the course and this report is: Refining Green Plants to Protein Cakes and other useful products in the African country Zambia.

The interest for ATO is how to refine the green plants to protein cakes to feed pigs. They already have a patent on this topic and a pilot plant doing this, but they wonder if there are other possibilities. Also they have a problem with some huge waste streams. This is where Shell's interested in. From the waste streams they want to make a high quality transport fuel.

In Zambia there are about 350 000 pigs [1]. This is relatively little compared to the 3.5 million cows in the country. This is mainly caused by the high price of pig-feed components as they now are imported from e.g. Argentina (310 dollars/ton for Soy cake at a protein concentration of 47%). If the price for protein cakes is lowered, it is possible that the amount of pigs will rise. With more pigs, the market for protein cakes will be bigger and bigger.

The most important criteria for the protein cakes are that they are harmless for the pigs and other cattle, and that they are much more cheaper than the current available protein cakes.

For the other products, it depends on the usage of the product. If grass fibres are combusted to electricity, only 5% water is allowed as a maximum. If they are used as cattle food, the restriction is the toxicity of the components to the animals.

If ethanol is produced, it should be fuel grade. This means not more than 0.01% water. Other components like sulphur and nitrogen are not tolerated above 1 ppm.

Sustainability

New processes always have to fulfil newest criteria on environmental issues. The process discussed in this report should fulfil the strongest relevant criteria requirements of the European Union. Important is the cradle-to-grave method. All components you take from the ground should also be putted back one way or the other. Especially the nutrients are very important in this process.

Marketing

At least 45% of the Zambian working population is engaged in agricultural and livestock production. In this context even when the majority of livestock production is oriented towards cattle and goat raising, pig production is seen as a promissory activity if the prices of the feedstock decrease and better sanitary conditions are implemented. Zambia is an underdeveloped country. From the total number of farms, 75% percent correspond to poor and very poor farmers with landholdings less than 1 ha, whose production is oriented towards self-consumption. 23.91% of farmers are in the class of emergent and medium scale, oriented towards subsistence and commercial agriculture, and less than 1% are large scale farmers engaged in commercial agriculture. With this in mind, it will be very difficult to implement a completely new process in such a agricultural based country.

2. Process Options & Selection

After a brainstorming session it was determined that for a scenario (also called a process option) the following building blocks need to be determined:

- Product market: This determines the scale of the project.
- Process market: This determines potential buyers for the process and the product.
- Feedstock: Different kinds of feedstock are available for the process, each with its own pros and cons.
- Products: Different products can be made from the feedstock, each with its own price and way of manufacturing. Products can also have different quality, leading to different kinds of options.
- Mobile vs. Stationary. Especially for this process this aspect is important. The principals wanted the possibility of a mobile process to be investigated.

During the brainstorm session the following table 2-1 was constructed with the different options for the above-mentioned building blocks.

Table 2-1: The different options for the building blocks of the scenarios. From every column 1 possibility is chosen. For the column 'Products' a choice is made for every product.

Product market	Process market	Feedstock	Products		Mobile vs. Stationary
1 Household	1 Household	Rangelands	Protein	Feed	All mobile
1 Community	1 Community	Planted grass		Food	All stationary
Pig farm	Pig farm	Planted legumes	Sugar	Feed	Semi mobile
Total Zambia	Independent company	Legume based pasture		Fuel ethanol	
	Slaughterhouse			Food ethanol	
	Government		Fibre	Feed	
				Electricity	
				Cloth/paper	
				Fuel	

Below are descriptions of the building blocks for the scenarios. Every aspect has been evaluated for the more promising parts. The combination of considered options can generate over 10.000 scenarios. Nevertheless, only the most feasible ones have been worked out and from them 4 scenarios were determined to be the most promising for Zambia.

2.1 Reasoning for the chosen scenarios

2.1.1 Product market / scale of process

1 household (4 pigs)
Demand from one household is too small, hence it is not considered for scenario definition.

A market of a community (150 households, 600 pigs)
Several communities with one process will be more attractive market. In that case the scale of the process comes to the scale of a pig farm. It is important to consider that pigs in a community are kept for personal use or selling in local markets. Hence it is very likely that pigs are fed with

leftovers rather than expensive feedstuffs. If the protein cake price is low enough, communities could be potential buyers.

A pig farm as a product market (about 5000 pigs, small scale production)
This seems to be the most interesting option. A farmer who is starting a pig farm on such scale is likely willing to invest in a stable supply of good protein, which leads to get good pigs to get good money from a slaughterhouse.

A market the size of whole Zambia (large scale production)
Since not all the 350,000 pigs currently in Zambia are fed with protein cakes, the scale of this process is initially set at 300,000 pigs, taking into consideration potential scale-up. This option is worth investigating, but since the process is much larger than the process for one pig farm, the investment costs will be much higher, as will the risks.

Accordingly, a market of one pig farm is determined to have the greatest opportunities. The second option considered is the market of whole Zambia, with 300,000 pigs.

2.1.2 Process market/process scale

1 household
It is not realistic that one household buys the process. The scale of the demand and its investment capacity is too small for this process.

1 community
Since a community is a group of poor farmers it is also not possible to get an investment of at least tens of thousands of euros. But with help of the UN or similar organisations they could perhaps afford it. Correspondingly, the focus of such a humanitarian aid project should also be shifted away from profit (money for a company) and towards self-subsidence value (a better living for the people in Zambia).

A pig farm
It is the most promising option. The owner of a pig farm is willing to invest in good and steady protein supply. In that case, a farmer produces the protein cakes for himself, and less transporting is needed compared with the independent company.

A slaughterhouse
They might be interested in this process. The main problem is that farmers can only trade with the slaughterhouse, and then are sandwiched within one company. Their position can easily get very weak in this case, and this will not really help the development of the country.

An independent company
It will be a better option. They have no other relation to the pigs produced so their business relations with the farmers will be healthier than that of a slaughterhouse. An independent company can either target the pig farm scale of the market, or the large-scale process. Because of the bad reputation of the stability of African countries an initial investment in a small-scale process is more likely.

Government of Zambia
The Zambian government is not in a good position for making this kind of investments due to short budget [1] and other urgent needs. Consequently it is not considered a potential buyer for the process.

In conclusion, one pig farmer that owns and runs the process itself is considered to be the best option. The second option is an independent company for a small-scale process, and the third option is an independent company producing at large scale.

2.1.3 Product options

The main part of useable components in grass consists of fibres, protein and sugar. Below is the description of the possible uses of these components.

Protein can be used as either pig feed or human food
Human food has higher requirements and more strict food laws to satisfy than pig feed. Since this process is rather new, it is recommended to start with the pig feed to evaluate the process in real life. If it is found out during the design that it is possible to make high purity protein, a recommendation will be made for future investigation into grass-based foodstuffs.

Sugar
Sugar to food grade ethanol
Alcoholic beverages can be made from many different crops. Since the core business of the owner is to make protein cakes, it is better to find a way to use the sugar to support this instead of creating the need to find a market for the new product. Therefore, no process will be designed for this.

Sugar to fuel-grade ethanol
Alcohol is produced from the sugar obtained in protein/sugar separation. After the separation the sugars are transported to a central location where the sugar from several farms is fermented to ethanol. It is the most promising option for sugar use in the large-scale process; furthermore, protein cake purity and price, also increases because of purification.

Sugars and fibres to fuel-grade ethanol
In this case ethanol is produced from sugar and fibres. These fibres must first be converted to a sugar soup; the rest of the process will be the same as the small-scale process. Since additional equipment and (developing) technology is needed, it could be a future option for the large-scale process.

Sugar to feed
Although it is possible to convert the grass sugars into ethanol, because of the high purity needed for the fuel ethanol, the purification costs per amount of ethanol will be significantly higher than that of the large-scale process. Pigs can easily digest sugar, so the best option is to leave the sugars in the cake to give energy rich protein cakes instead of separation from proteins (as long as is guaranteed that the protein content is high enough for the pigs).

Fibre
Fibre to electricity
Electricity is needed to run the process. Since it is quite likely that the pig farms are not connected to the power grid in Zambia, the process must make its own electricity or invest in a grid connection. The best options are to combust the fibres and the released heat to make

electricity. If any fibres are left after producing enough electricity to support the process, they can be fed to the transport oxen, since the fibres are digestible by those animals.

Fibre to ethanol
Fibre to produce ethanol is a feasible option. As mentioned in the sugar usage, sugar soup from fibre mixed with sugar from protein/sugar separation step can be fermented to ethanol. After purification, it can be transported to the farm as the energy provider for the process or sold to a fuel company to make profit. But the main problem is that chemical treatment or enzymes are added in conversion from the fibre into sugar. Both of them are very expensive, so question is whether these extra costs are less than the extra proceeds made. Thereby, chemical treatment is a very difficult and dangerous process and a big loss of acids and bases that can't be recycled. Another problem with ethanol production from fibres is that (part of) the produced ethanol must be returned to the farms for electricity generation.
So also for the large-scale process, making electricity from fibres is the best option.

Clothe or paper
If the quality of the fibre is very high or, if it can easily be made high enough at low enough cost, a recommendation will be made for future investigation into the use for cloth or paper.

2.1.4 Mobile versus Stationary

General disadvantages compared with identical but stationary units

Mobile units require more energy to work
The electricity to run will be more or less the same, but the transport of the process requires fuel. Fuel is needed in both options to transport the streams to and from the different units. Local processing will reduce process stream sizes, resulting in lower transport (energy) costs. An optimum has to be designed. Besides, it is important to consider that mobile units have larger downtimes (while they are transit), and mobile units always require larger investments than stationary ones.

Possibilities to use mobile units in the process
Production of electricity on mobile units is improbable. First of all, producing electricity on a mobile unit has a lower efficiency than production on a stationary one. On a truck the size of the electricity production unit is limited. Combined with the downtime, production of electricity on mobile units is inefficient. Furthermore, if electricity is not generated on a unit, it needs to be connected to a electricity source, with a rather long wire.

Ethanol production on a mobile unit is not realistic. The conversion of sugar to ethanol takes at the very best several hours, but more likely a day or two. This results in large vessels, which can't be transported easily. So for large-scale processes, fermentation from sugar to ethanol should be done in a stationary plant, which is supported by the power grid.

The only process step where a mobile unit could be feasible is cell breaking
This must be done within 10 hours of harvesting to be sure the pressure in the cells is still high enough to allow proper disruption. If the process is located far from the grasslands, it is necessary to break the cells in the grasslands, if the grasslands are close enough to the process, a totally stationary plant remains the preferred option.

When choosing the location of the plant, other factors, such as labour, water, electricity, roads, etc, need to be considered. Boundaries are: plant in the centre, or in the corner of the harvesting area. For large-scale scenarios, if the availability of grass is limited, not enough grass will be available in the area from which it could be directly processed at the stationary unit within 10 hours of harvesting. In this case mobile units are needed to convert the grass into fibre cake and a sugar/protein mixture. Ethanol can be produced in a central stationary plant, while electricity could be generated from the fibres.

If the amount of grass is not limited in this large-scale process, then an all-stationary plant suffices. An example could be that several small-scale farms combine their sugar water on a central location.

For small-scale scenarios, because of the lower grass requirement, it is more likely to find enough grass around the plant to allow processing within 10 hours of harvesting, a completely stationary plant is chosen.

2.1.5 Feedstock

Four different options are defined.

Natural rangelands
Natural rangelands are natural vegetation, composed of tall grasses forming a dense cover (specially under low tree densities) associated to trees forming savannah or wooded grasslands, the most common genera are Hyparrenia and Loudetia grasses [2], characterised by low productivity and low nutritive value [3].

The values used to determine yields and chemical composition correspond to natural rangelands without inclusion of legumes or use of fertilisers. The production, correspond only to the wet season. Costs of production are related to labour supply for weeding and cutting, since no fertilisers are used (more details in Table 2-2).

Planted grasslands
This refers to the planting of improved species of grasses with high nutritive value and high potential of production. Dry matter yields were determined only for the six months of the rainy season. Three species have been chosen: Napier Grass (Pennisetum purpureum K. Schumach.), Guinea Grass (Panicum maximum Jacq.), and Star grass (Cynodon spp). Grasses are assumed to be cut every 60 days (8 weeks) during the rainy season, and fertilisation could be applied after each cut, The recommendations for fertilisation include N and P, for establishment and maintenance of the sward. Fertilisation together with labour needs form the total costs of production of improved grasses. (Table 2-2)

Planted Legumes
Pure stands of tropical legumes were also analysed. For this purpose three species were selected: Desmodium intortum (desmodium greenleaf), Macrotyloma axillare (Archer), Macroptilium atropurpureum (Siratro). Production and chemical composition are considered also in the wet season. It is assumed that P, K, and Microelements fertilisation is needed to assure good yields. Fertilisation is used for establishment of the legume as well as for yearly maintenance. Legume fields could be cut every 3 months under Zambian conditions, which render two harvests per season per year. Total costs are based on fertilisation and labour requirements. (Table 2-2)

Legume Based Pastures

Legume based pastures are the mixture of legume species with grasses. This could be an option to get feedstuff of better quality, while lowering requirements of fertilisers than sole production of fertilised grasses. There are many combinations possible with the available species of legumes and grasses. Pastures considered for the project are fertilised with N for establishment and P for maintenance. As in the previous cases the total costs of production depend on the total amount of fertiliser and labour used. Cutting pattern will be the same as the one used for planted grasses, and estimation of dry matter production and chemical composition will be determined for the wet season.

Table 2-2: Dry matter yields, chemical composition and costs of production of rangelands, grasses, legumes, and legume based pastures (wet season) [4-7]

Feedstuff	YIELDS ton DM/ha/wet season	FM %	DM %	CP % of DM	CF % of DM	ASH % of DM	EE % of DM	NFE % of DM	Cost Euros/ton
Rangelands	5.6	75.0	25.0	5.6	37.0	6.0	-	-	21.5
Grasses	12.85	79.6	20.4	8.9	33.1	12.5	1.6	43.9	29.1
Legumes	11.33	72.9	27.1	16.0	29.7	8.9	2.3	45.3	21.3
Legume & Grasses	8.27	79.0	21.0	12.0	36.3	9.0	2.8	39.7	27.4

Legumes are the best option so far, one of the reasons is the high protein content they have that allows the use of less land devoted to green material production. For another criterion, economic, legumes represent the lowest cost of production. These two criteria that converge to legume production, allow for the minimisation of area under green material and costs of production, positioning legumes as the most suitable option for protein extraction. For a more detailed description of the feedstock for the process see chapter 5 about raw materials.

2.2 Selection of scenarios based on margins

For the calculations of margin, only product proceeds and raw material costs are taken into account. These calculations give the maximum profit possible for different processes. For the calculations, some feedstock and product scenarios were made. These scenarios depend on different inputs and outputs. In table 2-3 different inputs and outputs are given.

Table 2-3: Different inputs and outputs for the margin calculations

Grass input	Protein output	Fibre output
Range land grass	Protein cake low protein contents	Cakes (feed for oxes)
Cultivated grass	Protein high protein contents with ethanol from sugar	Electricity
Legumes		Ethanol
Cultivated grass with legumes		

The price for the low protein content protein cakes dependents on the type of the grass. The grass composition determines the amount of proteins in the cakes. Thus, the price of cakes depends on the protein contents. Also the stream sizes are different for the different kinds of grass. Appendix 1-3 gives the streams and the prices for the different raw materials and products.

Different combinations from table 2-3 in combination with the stream sizes and prices from appendix 1-2 give the margin per combination. The results from these calculations are shown in appendix 1-3.

The largest margin is reached with rangelands as input and high quality protein and ethanol from sugar and fibre. But for this process large investments are also needed. For the other processes only the legume as input gives positive margins, so it is decided to use the legumes as feedstock. Since apart from margins, also the total investment cost (and other factors) are important for the final decision on which scenario to work the tool PIQUAR is used (see paragraph 2.3).

2.2.1 Summary of the chosen scenarios

Taking all above considerations into account resulted in the scenarios described in table 2-4 below. Scenario III and IV are identical scenarios; the only difference is the owner of the process. In scenario III the owner is the owner of the pig farm, while the owner of the process is an independent company in scenario IV. The largest difference lies in the investment in the plant. A pig farmer already had to invest a lot in his pigs; an independent company only has to invest in the process.

Scenario III is a scenario in which the sugar of several small-scale plants is collected and transferred to a large-scale plant where the sugar is converted to ethanol, ethanol is then purified to fuel ethanol.

Scenario IV is the same plant as scenario III, but now the fibres are also collected at the central unit. These fibres are then converted to a sugar soup, which is converted together with the sugars to ethanol which is purified to fuel-grade..

The block diagrams of the scenarios can be found in appendix 1-1.

Table 2-4: Summary of the 4 scenarios

Scenario	Product market (pigs)	Process market	Protein	Fibre	Sugar	Mobile vs. Stationary	Feedstock
I	300,000	Indepen-dent company	Feed (High quality)	Electricity	Fuel ethanol	Stationary	Legumes
II	300,000	Indepen-dent company	Feed (High quality)	Fuel ethanol	Fuel ethanol	Stationary	Legumes
III	5000	Pig farm	Feed (Low quality)	Electricity	In cake	Stationary	Legumes
IV	5000	Indepen-dent company	Feed (Low quality)	Fuel ethanol	In cake	Stationary	Legumes

2.3 Scenario decision based on the PIQUAR method

To decide on which scenario to work a PIQUAR analysis was made [8].

2.3.1 Determination of criteria and weighing factors

PIQUAR is a tool to determine before a project starts what the most important factors for the design are. During the first meeting with the principals a list with pre-selected criteria was defined. One principal rated 11 criteria, the other 10. Both principals rated two identical criteria so a total of 19 criteria remained [appendix 12-1]. After that, the group only rated those chosen criteria.

When all criteria were rated, the criteria that the most people voted for were chosen first (where the vote of the principals counted double). When 2 criteria got the same number of votes, the one with the highest average rating was selected to be more important. The list of the 10 most important criteria is shown below in Table 2-5. The number 10 is suggested for use by the PIQUAR method.

Table 2-5: The 10 most important criteria found by using the PIQUAR method

	Criterion	Weighing factor
A	Minimal investment cost	0.29
B	Trusted by people living nearby	0.17
C	Low production cost of end product	0.13
D	Goal of the process must be clear in advance	0.11
E	Stable operation	0.10
F	Internal recycling of wastes	0.06
G	Potential for further developments determined	0.05
H	Demand driven	0.04
I	Heat integration	0.03
J	Based on proven technology	0.03

By individually rating all criteria pair wise, the PIQUAR method was used to give the weighing factor for each criterion, which can be found above. The calculations of these weighing factors are shown in appendix 12-2.

2.3.2 Choice of scenario based on PIQUAR

All 7 team members evaluated the 10 criteria above for the 4 scenarios. A number between 0 and 1 had to be given for every criterion. To determine the quality of every scenario, the average from every person for each criterion for each scenario was calculated. These averages were multiplied by their weighting factor and added to come to the amount of quality for each scenario. The results are shown in the Table 2-6 below.

Table 2-6: Values of unquality per criteria for each scenario and total amount of quality for each scenario

Criterion	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Minimal investment cost	0.16	0.18	0.06	0.05
Trusted by people living nearby	0.08	0.09	0.07	0.06
Low production cost of end product	0.05	0.06	0.04	0.04
Goal of the process must be clear in advance	0.06	0.07	0.06	0.06
Stable operation	0.03	0.04	0.03	0.03
Internal recycling of wastes	0.02	0.02	0.02	0.02
Potential for further developments determined	0.02	0.02	0.02	0.02
Demand driven	0.02	0.02	0.02	0.02
Heat integration	0.01	0.01	0.01	0.01
Based on proven technology	0.01	0.01	0.01	0.01
Quality	0.54	0.49	0.67	0.70

It can be clearly seen that on basis of the PIQUAR criteria the large-scale scenarios are much less favourable than the small-scale scenarios. The main reason is the high relative value of quality for the minimal investment cost scenario. In addition to this, under the instable political and economical conditions in Zambia, large investments are not a good option. Therefore the choice was made for the small-scale scenario.

2.4 Future Development

The potential market for pig feed in Zambia is sizeable (~300,000 pigs) and has high potential for growth. However, Zambia is a poor country, with a significant inflation (20%); any investments are risky, with a realistic chance that they will not pay themselves back. If the Zambian economy recovers, opportunities arise. The idea of the proposed project is to slowly build up a large process for the production of pig feed and fuel grade ethanol. This lowers the risk of running major losses, while keeping a chance for a head start when (or, if) the economy comes around.

The pathway for development is briefly discussed below, while the separate parts are explained further in the text.

Stage 1: Small-scale, on-farm protein production.

Low investment cost is the prime objective. Protein is not separated from sugars. The scale of the process will be 5000 pigs/unit, with protein cake, electricity and heat as products.

Stage 2: Small-scale pilot plant for ethanol production

Several (3-4) conveniently located units of step 1 will be upgraded to contain a protein/sugar separation step. The sugars will be concentrated, and transported to a small ethanol production plant. The objective of this plant is to test the market for ethanol.

Stage 3: Large, central ethanol production

Once enough farms are equipped with the grass conversion units, all sugars will be processed at one full-scale ethanol production facility.

Stage 4: Fibre conversion

If everything goes well, and conversion of fibre into ethanol is promising enough, the existing facility can be expanded with a fibre conversion step. If the technology develops enough, fibres will be converted to sugar on-site, which will be added to the sugar-pool.

Each of these stages corresponds to a viable process conformation. This means that if there is too little incentive to go from for example the second to the third stage, other groups of farmers can still decide to make smaller scale ethanol plants.

A possible (optimistic) timescale for this project would be:

Year 1:	Building of first plant, first harvest
Year 2-3:	Building of several additional units.
Year 4:	Decision of a few process owners to invest in a small-scale ethanol production facility. Start of build.
Year 5:	Commissioning of pilot plant, test sale of ethanol-based fuel in Zambia.
Year 9:	Start of build of the large-scale facility. Creation of infrastructure for concentrated sugar and ethanol.
Year 10:	Commissioning of large-scale plant.
Year 14:	Optimizing of gasifier operation for alternative fuels. Alternative fuel is needed since the fibre now used for energy is to be used for ethanol.
Year 15:	Expansion for fibre conversion, either on small- or on large-scale.

This schedule is highly speculative. The timescale in which the first additional units will be built depends on how the first plant operates. The third step partly depends on where these additional units are built. If a handful of facilities are built within a critical density (10-20 km radius, depending on roads etc.) and near to (cooling) water, there is more chance of success of the pilot-plant.

If the pilot-plant works well, a large-scale plant could be built. If the pilot-plant works very well, other units could cooperate and invest in a similar small-scale plant, rather than invest in the large one.

Stage 1 – grass conversion
A small facility (capacity of 5000 pigs) will be built, consisting of a disc-refiner, gasification-based Combined Heat and Power (CHP), some evaporators and other auxiliary equipment. Legumes will, after washing, be passed through the disc-refiner. The plant cells will be disrupted, and their contents washed from the remaining solids (fibre). The fibre is to be dried, gasified and combusted to generate heat and electricity in the CHP. The water will be evaporated from the rest of the cell contents, to produce a sugar/protein mixture with a high enough protein content to allow use as pig feed. Identical units of this type will be built on demand.

Stage 2 – small-scale ethanol production
Several (conveniently located) units from stage 1 will combine efforts to produce ethanol. After the first evaporation, protein will be separated from the sugars, fats and minerals using ultra-filtration, and concentrated, to form a high purity (90+%) protein cake, while the sugars are concentrated. The concentrated sugars will be transported to the ethanol-production plant, where they will be fermented. After fermentation, the ethanol is to be purified to fuel-grade (See also appendix 2-2).

The fuel-grade ethanol will be incorporated into the then existing fuel-infrastructure. The market will be closely monitored, and evaluated for growth potential. If sufficient potential is there (and if the economy is upwardly mobile again), the decision to scale up can be made. By this time ample units from the first stages would be in operation, to allow production of a full-scale plant.

Stage 3 – large-scale ethanol production
The third stage is largely identical to the second stage, but then in a larger (~300,000 pigs, 60 units) incarnation. All units will refine the protein, and send their concentrated sugar to the central plant. Depending on the market research, the size of the facility will be either one big plant, or a few plants in the order of magnitude of the pilot-plant.

Since large mass-flows between units and plant are required, development of a suitable infrastructure for transportation is important. To give a few examples: all farms could deliver their sugar directly to the fermentation, or they could deliver the sugar to one of a few gathering points, from where the sugar is brought to the fermentation. Fermentation and pre-distillation could be performed at the gathering points, with watery ethanol being purified at a central location.

Transport can be done by truck, by pipeline, or by a combination of both. Due to the fact that the farms in Zambia will quite likely be scattered across an area approximately four times the size of the Netherlands, much can be gained in optimising these logistics.

Stage 4 – fibre fermentation
Conversion of fibre into sugar is a future option for expansion, depending heavily on the development of the yeast/cellulase technology. The maximum obtainable ethanol from fibre is about half of that obtainable from the more digestible parts, which makes it an interesting additional feedstock.

However, in protein cake production, quite some heat is needed, and nearly all (80%+) fibre is initially needed to heat and power the process. Thus, in order to incorporate fibre into the ethanol branch of the process, alternative fuels must be found. If the gasifier is designed robustly enough (variable temperature ranges, easily controlled flow rates), almost any organic matter can be used: Sewage and domestic waste can be considered, but also specially grown energy crop. Depending on the state of technology, the fibre conversion can be conducted at either farm or the ethanol plant. Other sources of energy, such as sun-boilers, or photovoltaic cells could be used.

Another option to increase ethanol production would be to work with a grass species with a low protein, and higher sugar content, thus increasing the sugar to protein ratio. This would result in larger harvesting areas and costs, and the need to increase capacity of the facilities. However, the expenses of developing fibre conversion would be avoided, since no fibre needs to be converted to ethanol.

3. Basis of Design

3.1 Description of the design

The original design was intended to investigate the possibility of a mobile facility to refine green plants into pig feed. Very soon it was found that the weight of process units would become too large to be mobile. If small units were chosen the area covered would be so small that mobility was not needed. Therefore a design will be made for a stationary, small-scale process in Zambia. The principals chose Zambia because of the large potential market for protein cakes. At this moment a relatively small amount of pigs are present because of high protein import prices, and diseases. If a process, which is able to produce protein cakes at a lower price, can be designed it would be expected that the number of pigs would increase, provided that adequate support exist from animal health services.

As is stated in Chapter 2 the real design will be made for the small-scale scenario, because of the lowest initial investments. In this scenario legumes will be cultivated and harvested. The legumes will be separated into fibres and low quality protein cakes. For the future scenarios with ethanol production only a rough design will be made, in order to give an estimate of the feasibility of ethanol production.

3.2 Process & Product definition

3.2.1 Choice of process to be designed

In Chapter 2 the different building blocks for scenario construction have been discussed. The design will be made of a stationary, small-scale plant. This plant will produce enough protein cakes for a pig farm for 5000 pigs. The small-scale process was chosen because of the low initial investment costs.

The potential and ideal buyer for the process would be an independent company and not a slaughterhouse. This could avoid creation of monopolies where slaughterhouses are in the position to manipulate negotiations.

The chosen raw materials for the process are pure stands of legumes. In the first phase of the design legumes were chosen based on economic and productivity criteria.

The products made on the small scale are protein cakes, from the protein and sugar fraction in the legumes, and electricity from the fibre fraction. Once the legumes are harvested they will be separated in their fractions. After the fractionation of the legumes, the fibre (and non fractionated legume cells) will be separated from the other fractions. Since the ratio of protein over sugar and ashes is high enough to give protein cakes enough protein, the protein, sugar and ash fractions will not be separated. All these fractions together will be dried, stored and sold as protein cake. The fibre fraction will be dried and used for electricity generation. This step is really needed at the small-scale scenario. The farms will be located in the vicinity of a larger city, because they need to bring their pigs to the market within a reasonable time. But in Zambia there is virtually no power grid [1]. Building a power line from the city to the plant is not an option because of the high costs and the vulnerability of the line to sabotage, weather influences and illegal tapping of electricity. This means that electricity must be produced at the farm and fibres are the preferred choice for burning.

The only process steps in the process mentioned above are harvesting, cell breaking and separation. In none of these steps reactions occur, so there is also no information about stoichiometry, kinetics and catalysts.

In appendix 3 the process flow scheme (PFS) of the process is shown. During the dry season biomass production could be lower, and we are assuming that no legumes are harvested in the dry season. This result in a half-year production time, in other words the process is not continuous. A second reason why a fully continuous process is not possible, is that the breaking of the legume cells must happen within 10 hours of harvesting. After this time the cells have lost too much of their turgor to be relatively easily broken. In appendix 7 the non-continuous diagrams are shown.

3.2.2 Future scenarios

Although the minimal investment cost criterion indicated that the small-scale scenario is the preferred one, the principals are interested in the possibilities of an ethanol producing plant. It is not very likely that ethanol will immediately be produced at the size of a full-scale refinery, again because of the high investment costs. As described in the future scenarios in chapter 2, the step between a small-scale farm and a full-scale ethanol plant is a small-scale ethanol plant. The feedstock for this plant is the sugar fraction (separated from the protein fraction) combined from 3 farms.

In order to make this scenario work, a sugar/protein separation unit must be installed on the small farm. On a central site, the sugar fermentation to ethanol and the ethanol purification step(s) must be constructed. This site must be near a cooling water supply. Since there are a lot of rivers, lakes and small streams in Zambia, this is not expected to be a problem.

The owner of this process can either be an independent company, or one of the owners of the small-scale protein producing plant. As in the small-scale process, legumes will be used as the raw material for processing.

By removing the sugar from the sugar/protein mixture, a higher quality protein cake will be produced. Fibre is still used to generate electricity, because electricity is still needed at the small plant and conversion of fibres to sugar soup is costly (acids or enzymes). Also, the fibres would be used for conversion to ethanol, a part of the produced ethanol woulod have to be burned for heat and electricity generation. Another disadvantage would be the fact that part of the electricity generating units on the farm would no longer be used.

A PFS of the ethanol process can be found in appendix 6a. For the farm part the same non-continuous diagram applies. The large-scale process will be done full continue, so no batch diagram of that is given. Because only rough estimates for the profitability of an ethanol producing plant are calculated, no attention was given to a batch diagram of fermentation. Only a total vessels volume is used.

3.2.3 Thermodynamic properties and reaction kinetics

In the process, no reactions take place in the small-scale scenario. For the ethanol scenario, the conversion of sugar into ethanol is the only reaction that takes place. The kinetics and other important data for this reaction are described in chapter 4. The tables with pure component properties are in appendix 2-1.

3.3 Basic assumptions

3.3.1 Different feedstock compositions

Four major options, differing in crops and method of management, are available. They are rangeland, normal grasses, legumes and the mixture of legumes and grass. Composition of these crops is usually given in crude protein (CP), crude fibre (CF), ashes, ether extracts (EE) and nitrogen free extracts (NFE).
No dry matter or EE content was found for rangelands, so they were assumed to be 20% and 2% (comparable to the other crops) respectively. Rangelands also did not have NFE values. Their NFE is assumed to comprise the rest of the dry matter content.

NFE is assumed to be mainly sugars and other digestible organics. EE (fats, solids) are assumed to be 50% digestible, 50% inert. For mass balances, ashes, NFE and EE have been combined to Ash (ashes + 0.5 EE) and Sugar (NFE + 0.5 EE).

Table 3-1: Feedstock compositions

	Legumes	Rangelands	Cultivated grass	Legume - grass
Dry matter	27.10%	20.00%	20.40%	21.03%
Ash	2.67%	1.38%	2.75%	2.10%
Protein	4.34%	1.12%	1.82%	2.77%
Sugar	12.58%	10.08%	9.11%	8.45%
Fibre	8.05%	7.42%	6.76%	7.64%

3.3.2 Protein cakes needed to feed pigs

A pig needs, on average, 2.5 kg feed every day. About 13% [1] (0.325 kg) of feed should be protein components. This makes the annual protein consumption of one pig: 118.625 kg.

In scenarios 1 and 2 (large scale), we attempt to feed the 300,000 pigs in Zambia, for which 35 kton of pure protein per year is needed.
In scenarios 3 and 4, a plant should produce enough feed for 5,000 pigs (0.593 kton of pure protein). On such a small scale, fuel production is relatively expensive, which means that sugar-protein separation is not required, as long as the feed has ample protein content (13%+). This means we need to produce at least 4.56 kton of protein cakes per year.

3.3.3 Grass needed for production

According to the assumption of grass composition and protein cakes we produce per year, the amount of grass (or legumes) needed can be worked out. Feeding 300,000 pigs using legumes (4.3% protein) as feedstock, around 1,000 kton/a is needed. Using cultivated grasslands (1.8%), we need more than twice as much (~2,300 kton). The small scale requires 16.2 kton/a and 38 kton/a respectively.

3.3.4 Plant capacity

The small-scale plant will be designed and the feedstock is legumes, so the plant capacity is 16.2 kton per year. More explanations of the streams entering and leaving the system are described below.

It is not possible to let the whole process run continuously throughout the year. Legumes (and other feedstock) will be harvested during the rain season, which lasts half a year. Thus, the process can only run for 180 days.

The cell disruption must take place within 10 hours of harvesting. Harvesting can only be done when there is sufficient daylight, which is assumed to be from 6 in the morning till 6 in the afternoon, because Zambia is located quite close to the equator. So, in a full continues cell-breaking process, the maximum time between harvesting and cell breaking is 12 hours. This is unacceptable, so the cell breaking will only be done during 2 shifts of 8 hours. As is shown in appendix 7, the harvesting starts at 6 and it is assumed that the first legumes enter the process at 7. This means that the cell-breaking step ends at 23:00. The rest of the process will run continuously for 180 days.

3.3.5 Location

The plant(s) will be built in Zambia. Most likely in the central region, since the majority of pigs resides there at this moment. This region also has more suitable conditions in terms of infrastructure and market development. For future development the North region could be considered as a good option (see figure 5-1). The preferred site will have access to clean water, which is needed for washing and dilution at start up of the process. Once the process is in steady state more than enough water will be produced in the process itself, because 70+% of the feedstock is water.

3.4 Battery limit

Inside the battery limit are:
The transport of the legumes from the fields to the plant
The plant where the cells are broken, protein cakes are produced from sugar, protein and ashes and the electricity production from fibres
The storage of the protein- and fibre cakes, ashes and water
This is also shown in appendix 3 where a black line is drawn what defines the inside of the battery limits.

This means that the pig farm is outside the battery limit, because another company owns this farm. It also means that the produced protein cakes leave the battery limit and that manure from the pig farm is coming into the battery limit.

A special case is the legume fields. These are not considered to be inside the battery limits, but a study still had to be made how and when the legumes grow.

3.4.1 Definition of in- and outgoing streams

The in- and outgoing streams are defined in table 3-2 and 3-3.

Table 3-2: Process streams going into the battery Limits

Ingoing Streams

STREAM Nr. :		101,102		304	
Name :		grass feed		air in	
COMP		ton/a	kg/s	ton/a	kg/s
Water					
grass		1.62E+04			
Ash					
Protein					
Sugar					
Fibre					
O2				7.04E+03	
N2				2.32E+04	
CO					
CO2				1.38E+01	
CH4					
H2					
Total flow	ton/a	1.62E+04	1.04E+00	3.02E+04	1.94E+00
Enthalpy	kw	0.00		0.00E+00	
phase	L/V/S	S		G	
Press.	bara	1		1	
Temp	oC	25		25	

Table 3-3: Process streams going out the battery Limits

Outgoing Streams

205		309		321		323		324		403,404		506		507	
protein cake		fibre out		cartridge ash		ash out		engine exhaust		wastewater		protein dryer exhaust		fibre dryer exhaust	
ton/a	kg/s	ton/a	kg/s	ton/a	kg/s	ton/a	kg/s	ton/a		ton/a	kg/s	ton/a	kg/s	ton/a	kg/s
1.34E+02		1.43E+01						6.41E+03		7.47E+03		1.26E+03		2.64E+03	
0.00E+00		4.51E+01													
3.47E+02		1.24E+00		4.01E+00		8.09E+01		4.05E-02							
5.63E+02		2.00E+00													
1.63E+03		5.81E+00													
0.00E+00		7.44E+01													
								4.26E+02							
								2.31E+04							
								1.74E+03							
2.68E+03	1.72E-01	1.43E+02	9.18E-03	4.01E+00	2.58E-04	8.09E+01	5.20E-03	3.17E+04		7.47E+03	4.80E-01	1.26E+03	8.09E-02	2.64E+03	1.70E-01
22.73		0.00E+00		0.01		0.16		72.99		1.00E+01		186.43		401.13	
S		S		S		S		G		L		V		V	
1		1		1		1		1		1		1		1	
70		25		40		40		55		30		50		80	

The stream numbers refer to the numbers in the Process Flow Sheet (appendix 3 and 4).

4. Thermodynamic properties and reaction kinetics

4.1 Thermodynamics Models

Phase equilibrium data are needed for the design of all separation processes [1-5]. Experimental data have been published for several thousands of binary and many multi-component systems. However, no universal equation is available for nonideal mixtures to compute values of the thermodynamic properties such as density, enthalpy, entropy, fugacity and activity coefficient as functions of temperature, pressure and phase composition. Instead, there are two types of models to calculate phase equilibrium: (1) P-V-T equation-of-state models (2) activity coefficient or free-energy models. These are based on constitutive equations because they depend on the constitution or nature of the components in the mixture.

4.1.1 PVT model equation-of-state

The equation-of-state method is used to describe both liquid and vapor phase behavior. A large number of such equations have been proposed, mostly for vapor phase. It is recommended to apply it for weak non-ideal solution, such as most hydrocarbon and light gas mixture systems at high, moderate or low pressure (at least not below atmospheric pressure). This method is applicable for systems where the interaction of the components in the liquid phase is assumed to be minimal.

In small scale process, fiber will be converted to gas mixture and char in the gasifier. Gases consist primarily of carbon monoxide (CO), carbon dioxide (CO_2), and hydrogen (H_2). Hence PVT equations of state model are applicable to the gas mixture. Appropriate choices of the models depend on the components in the system, temperature, pressure, and the availability of parameters. It can be assumed that gasification process is operated at low or moderate pressure (below than 5 bar). The following models are most applicable.

If the operating pressure is 1-2 bar, ideal gas model will be adopted.

$$PV = nRT$$

If the operating pressure is 2-5 bar, the Virial equations model will be adopted.
Virial equation is:

$$Z = 1 + \frac{B}{V} + \frac{C}{V^2} + \frac{D}{V^3} + \ldots$$

For non-ideal species, at low pressures

$$\frac{PV}{RT} = 1 + \frac{BP}{RT}$$

B is needed as a function of T and species

After investigation, gasification is operated at 1 bar. According to the limitation of the models, ideal gas model is most applicable.

4.1.2 Activity coefficient model

Activity coefficient models are based on Gibbs free-energy models and are used to predict liquid properties such as activity coefficient and other excess functions. It is applicable for ethanol/ water separation.

In the large scale process, ethanol is produced in fermentation. After fermentation, an ethanol solution, with small amount of ash, substrate, biomass, sugar will be purified. It is a liquid-solid mixture, but the solids can be removed before the distillation step. Sugar takes an effect in separation of ethanol and water. Nevertheless, due to the small amount, its effect can be neglected. Therefore only ethanol and water are present in the distillation column during calculations.

The following table shows and compares five models.

Table 4-1 Activity Model Applicability

	Margules	VanLaar	Wilson	NRTL	UNIQUAC
Binary	OK	OK	OK	OK	OK
Azeotropic	OK	OK	OK	OK	OK
Polar	NO	NO	OK	OK	OK

Ethanol/ water is non-ideal, polar and azeotropic mixture. According to the table, Wilson/ NRTL/ UNIQUAC models are the proper ones for the separation of ethanol/ water.

4.2 Thermodynamic data

4.2.1 Reaction enthalpy data

The reaction enthalpy can be calculated from the heat of formation of each component at reaction temperature. All the data needed is in the table of pure component properties in appendix 2. From that, whether the reaction is exothermic or endothermic can be determined.

4.2.2 Specific heat data

Typical constant pressure specific heat (at 1atm, 25°C or different temperature) for each component can be obtained from literature such as some handbooks or from ASPEN PLUS simulation engine.

4.2.3 Comparison of the data:

T/x and x/y at constant pressure diagrams are produced for the key components. When comparing Wilson/ NRTL/ UNIQUAC models, which are applicable for separation of ethanol/water, results don't differ too much. Hence, one of the three models was chosen to make the comparison with real data. The following graphs are for Wilson model obtained from ASPEN PLUS simulation engine.

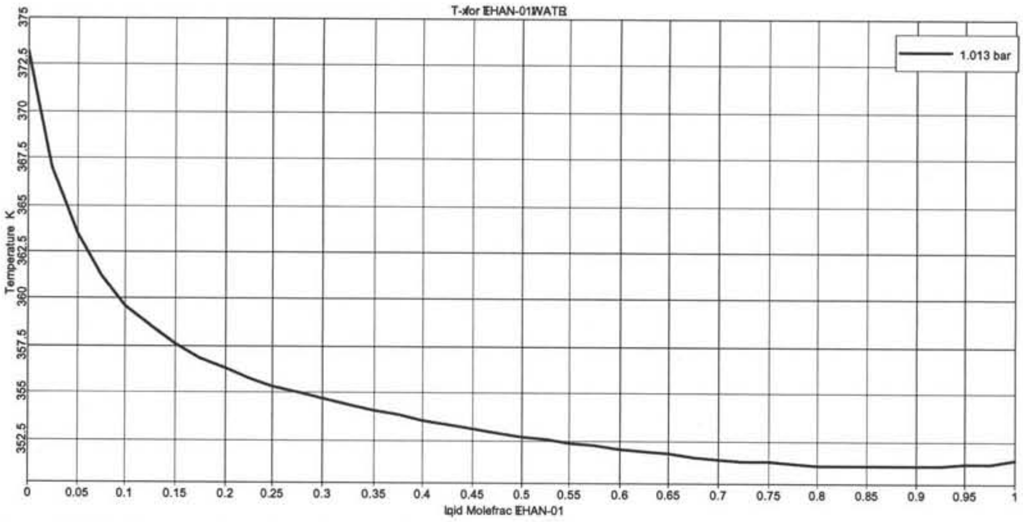

Figure 4-1 T/x diagram of an ethanol/water mixture at p=1.013 bar

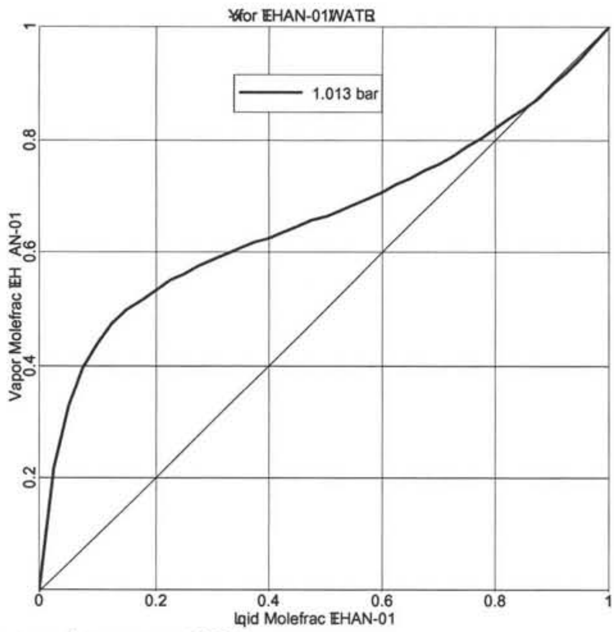

Figure 4-2 x/y diagram of Ethanol/ water mixture at p = 1.013bar

4.2.4 Validation of Method

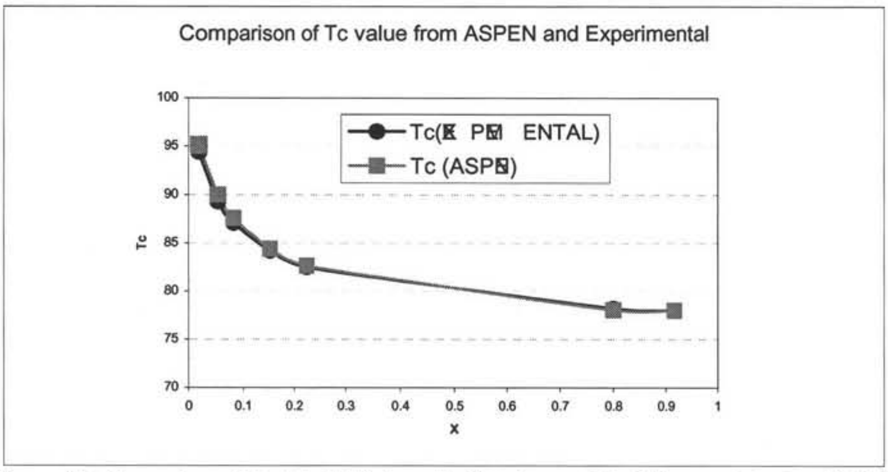

Figure 4-3 Comparison of the data (T/X) from the literature and the Wilson model using ASPEN [4].

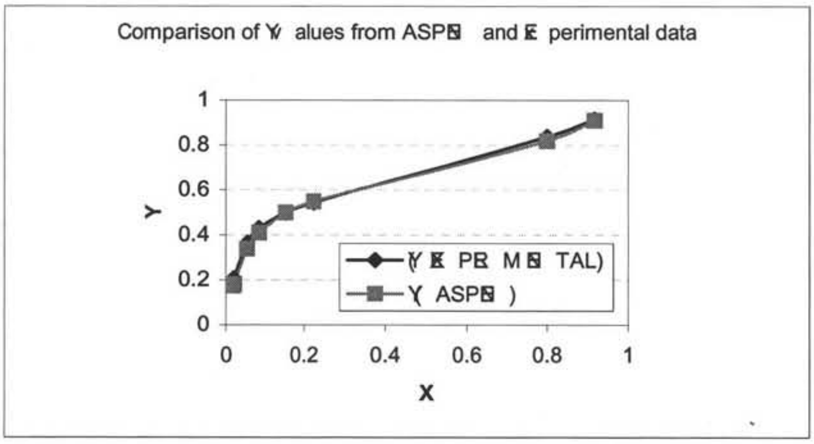

Figure 4-4 Comparison of the data (X/Y) from the literature and the Wilson model using ASPEN.

Difference of data from literature and Wilson model is acceptable thus Wilson model for Ethanol/ Water separation is valid.

4.3 Reaction kinetics

The reactions of ethanol fermentation and gasification are complex. Thermodynamic data on those two subjects are limited, and formal reaction kinetics cannot be expected as for normal chemical reactions.

4.4 Pure components properties

Data of pure components properties are obtained both from websites and handbooks as shown in the references [6-11].

For the toxicity data of chemical components, since all the components present in our process do not have high toxicities, data such as LD50 or LC are not available. There are no experiments done for it currently or if LD50 or LC is available, the data is for the animals, such as rats, but not for human beings (see chapter 11).

5. Raw Materials

5.1 Zambia, general characteristics

One of the countries of sub Sahara Africa, characterised by tropical climate moderated by altitude and tropical vegetation. Zambia has an area of 752,615 km^2. An average altitude of 1200 m.a.s.l (meters above Sea Level), that varies between 329 and 2301 m.a.s.l. It is one of the most urbanised countries with more than 40% of its 10.28 million inhabitants living in the cities like Lusaka, Livingstone and along the Copperbelt (following the railway and road systems). Also almost all commercial agricultural activities are developed in this area, since farmers in this area have relatively good access to urban markets [1].

Agriculture is considered the potential driver to develop the weak economy of the country. In this context, there are many activities related to production of crops and livestock. Farmers are characterised as small and medium size farmers (less than 20 ha) and large scale (more than 20 ha), see table 1 Small and medium size farms represent more than 90 % from the total households and within this group the great majority practice subsistence agriculture on less than 5 ha of land (poor and very poor farmers) [2]. Within livestock production, the main activity is extensive production of cattle and goats, which rely on natural and sown grasslands. Nevertheless, significant cattle losses have been experienced in recent years due to livestock disease, which has been attributed to declining rural services. Poultry and pigs are noted as potentially profitable for poorer producers if the cost of feeds and occurrence of diseases make it viable [1].

Table: 5-1: Types and characteristics of farmer classes in Zambia.

Characteristics	Small Scale	Emergent	Medium scale	Large scale
Number of farmers	459,000	119,200	25,230	740
% from the total	76 %	19.72 %	4.17%	0.12 %
Area per holding (ha)	0.5-0.9	10 - 20	20 - 60	> 60
Crops Grown	Food Crops	Food / cash crops	Food / Cash crops	Cash crops
Production Focus	Subsistence	Commercial/ subsistence	Commercial/ subsistence	Commercial
Source: [1]				

The country is divided in four agroecological regions based on rainfall, soil type and vegetation.

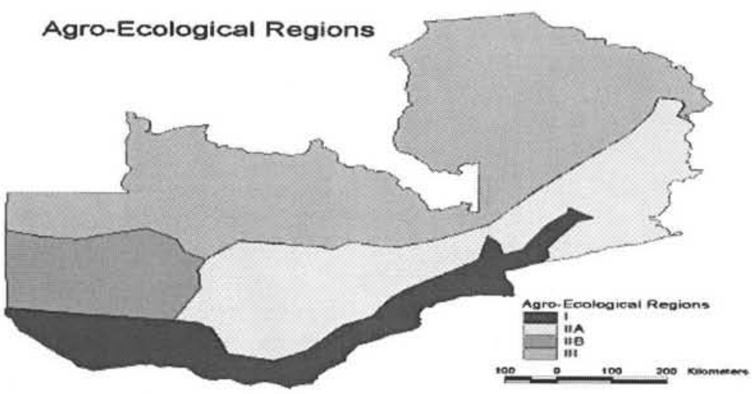

Figure 5-1: Agro-ecological zone I: Rainfall <800 mm per year; Agro-ecological Zone IIA: Rainfall 800-1000 mm per year Agro-ecological Zone IIB: Rainfall 800-1000 mm per year; Agro-ecological Zone III: Rainfall >1000 mm per year

The distribution of rains follows an almost unimodal pattern, with rains starting in October and ending in March or April. Three main seasons occur in the country based on rainfall and temperature [2]:

The Hot dry Season August to November
The Hot wet Season November to April
The Cold Dry Season April to August

5.2 Grasslands in Zambia.

In Zambia there are three well-defined regions, which are based on climate, soils and vegetation. Agro-ecological conditions (especially rainfall) will determine to a great extent production and quality of grasses. Hence, this should be taken into account for the determination of the species more likely to grow in each region. Production varies spatially and temporally. The main factors affecting production are annual rainfall, shading by woody plants and soil type, see table 5-2. Chemical composition change seasonally under rain fed conditions. Crude fibre content increases with plant. In contrast, the crude protein content of grasses is highest during the early growing season (November /December) and lowest during the dry season [3]. Other important factors influencing production and composition are management and use of inputs. It is important, in this sense, to distinguish natural grasslands from sown grasslands, and level of input use.

Table 5-2. Seasonal changes in dry matter (DM), crude protein (CP), crude fibre (CF), and ash of ungrazed rangeland on sandy soils at Grassland Research Station. (Zimbabwe)

Month	DM (kg ha^{-1})	CP (g kg^{-1})	CF (g kg^{-1})	Ash (g kg^{-1})
December	228.7	85	333	59
January	571.6	71	352	66
February	1017.7	50	384	60
March	1360.7	51	374	63
April	1462.7	41	395	54
May	1053.6	40	384	57
Source: [3]				

Potential grass production depends on agro-ecological conditions, especially rainfall. In arid areas (rainfall less than 400 mm/year) there is no cost effective technology for improving dry matter production or quality by sowing grasses or legumes, besides responses to fertilisers are too small to justify their use. In semiarid and sub-humid areas (600 –1200 mm/year) there are better opportunities to improve production and quality in rangelands, fallow or mixed crop/livestock systems. This enhancement is based on introduction of improved grasses and legumes.

Considering the characteristics of ecological regions, region II and III where chosen as more suitable producers of grass. Region I is the driest region in the country and the low rainfall is a limitation for grass production and quality. Region II and III have higher precipitation, and hence better possibilities to sustain production. In region II there is also a higher concentration of agricultural activities, population, and higher development of the market. This is caused by better development of infrastructure in this zone (roads, rail line) and also better soil quality. The higher number of households keeping pigs is also localised in zone II. Region III has more rainfall (over 1000 mm) and hence, it has greater potential for grass production, nevertheless the quality of soils is poorer (leached soils) and large areas are natural forests, fact that should be taken into account for the determination of the more suitable species to grow in this zone, as well as management of the sward.

5.2.1 Chemical composition of grasses

The nutritive value of grasses and other vegetation used as fodder is expressed in terms of chemical composition. The characterisation of chemical composition is done through the division of the feedstuff into fractions. The most common one is the division of the feedstuff in five fractions –Weende system- (see table 5-3). Alternative measures of feedstuff composition include the division of the feedstuff in cell contents and cell wall contents, where the cell contents include soluble sugars, carbohydrates, starch, pectin, non protein N, Protein, Lipids, Other soluble.

Table 5-3. Fractions in which feedstuffs is divided, their abbreviations and methods of extractions

Fraction	Abr.	Method of extraction
Crude Protein	CP	Kjeldhal Nitrogen and multiplication of N value by 6.25. Not an estimation of true protein since it includes other Nitrogen compounds.
Crude Fibre	CF	Extraction with ether, sulphuric acid and Sodium hydroxide.
Ether Extracts or fats	EE	Extraction with anhydrous ether
Ashes	ASH	Total combustion
Nitrogen Free Extracts	NFE	Subtraction of CP,CF,EE,ASH from the sample weight.
Source: [4]		

Cell wall contents include Hemicellulose, Cellulose, Heat-damaged protein, Lignin, Keratin, Silica [4]. The Weende system will be used for prior estimations on chemical composition of grasses and legume species to be used in the preliminary calculations for the project.

5.2.2 Natural Grasslands

In Zambia natural grasslands are dominated by *Hyparrhenia* spp. and *Loudetia* spp grasses combined with other species depending on the rainy pattern and altitude. *Hyparrhenia* spp rangelands are more in the north and eastern part of the country spread along region I and II. They are composed of tall grasses forming a dense cover (especially under low tree densities) associated to trees forming savannah or wooded grasslands. These grasses are more common between 450 to 1.500 m.a.s.l. and rainfall between 600 and 1500 mm [5]. *Hyparrhenia* species grow very fast when the rainy season starts, and quickly form tall fibrous plants with low nutritive value.

The other type *Loudetia* spp, is found towards western Zambia on Kalahari sands. This vegetation is composed of tall grasses forming a sparse cover associated to trees (higher densities) forming wooded grasslands. *Loudetia* spp rangelands also spread along region II and III. The range of altitude is between 900 and 1.500 m.a.s.l. and rainfall between 610 to 1400 mm during November to April [5].

Natural pastures in Sub Sahara Africa are characterised by low nutrient value, even under good management. In order to survive grasses, grow rapidly during the rainy season but they become fibrous after two months. The amount of available grass can be influenced to some extent, by controlling grazing and / or cut management, regrowth and pattern of rainfall, but the overriding quality constraint cannot be overcome. In the case of cattle production supplementary feed is needed.

Information on yields and composition on rangelands exists in some countries in Africa, but was not directly available for the case of Zambia, hence yields and composition of grasslands in a sandy soil in Zimbabwe were used as a proxy of production and composition in Zambia. The values for yields will be taken from table 5-4, and the values for the different fractions will be the average of the fraction during the six months of production (also see table 5-4).

Table 5-4: Dry matter production and chemical composition of rangelands, improved grasslands, legumes and legume based pastures.

YIELDS ton DM/ha/year	FM %	DM %	CP % of DM	CF % of DM	ASH % of DM	EE % of DM	NFE % of DM
5.6	75	25	5.6	37	6	-	-
Source: [3]							

5.2.3 Planted Pastures

Planted pastures could range from unfertilised and non-irrigated pastures to highly fertilised and irrigated pastures [3]. The first criteria for the selection of the potential species to be used is how well are species adapted to agroecological conditions in Zambia see table 5-5. Considering that the objective is to maximise the production of protein from vegetable sources (in this case grasses & legumes), dry matter production and protein content are the second criteria used to determine the most suitable species. Other aspects of management like suitability for cut & carry, type of pasture (annual or permanent pastures) and growing habit, are also important for selection.

The estimation of the production and composition of grasses have been done using data from literature of grass production in the tropics. In many instances, research on grasses about variation in yields a composition has been carried out in countries with different rainfall patterns and types of soils than the ones found in Zambia. Nevertheless the data could be useful to make estimations for the existent conditions.

In general grasses have more potential for biomass production but lower protein contents than legumes. Grasses have good responses to heavy N fertilisation; hence highly fertilised grass could produce more biomass and protein than a legume, without water restrictions. This type of production relies in high investments (purchase of fertilisers). In the case of tropics and related to cattle production, these systems are more suitable for dairy production rather than beef production, due to the higher returns which could be got from dairy more than beef. [6].

Chemical composition and yields of grasses varies dramatically with age and water availability as can be seen from table 5-2. In general the younger a grass is cut or grazed, the lower the dry matter yield and the higher the protein content. As the grasses get older, dry matter production increases, (which is logical, considering that the grass has more time to develop leaf and create more biomass), but the protein content decreases.

Table 5-5: List of suitable species to grow under Zambian conditions that could be used for protein production.

Scientific Name	Soils	Rainfall	Altitude	Type of pasture	Suitability for cut and carry
Grasses					
Napier Grass *Pennisetum purpureum* K. Schumach.	wide range	> 1000		Short Ley	Yes
Guinea Grass *Panicum maximum* Jacq	wide range	> 800	< 1500	Medium Ley	Yes
Star grass Cynodon spp	wide range	> 650	< 1500	Permanent	No
Rhodes Grass Chloris gayana	sandy clays	> 800	> 1000	Short Ley	yes
Legumes					
Desmodium Desmodium intortum	wide range	> 800	> 1200	Permanent	no
Siratro Macroptilium atropupureum	sands/sandy clays	650 - 1000	< 1500	Permanent	no
Macrotyloma Macrotyloma axillare	sands/sandy clays	> 800	> 1000	Permanent	-
Source: [3, 7], Fredy Baijukya personal communication (Tanzania)					

Pure stands of legumes could also be used to produce protein. Reported yields and protein content depend on management conditions, to fertiliser and water supply, even though legumes are more resistant to drought conditions than grasses [7]. Yields in dry matter terms are not going to exceed the ones achieved by fertilised grasses, but the protein contents are higher. Fertilisation of legumes is mainly regarded to P, K and Mo supply, N supply has negative effects since it suppresses the N fixation need of the legume. Nevertheless P, K, Mo fertilisation is a requisite to assure good performance of legume crops, specially under the conditions of poor soils in tropics [6]. Protein content declines slowly as the plant get older; this fact could be related to the continuous supply of Nitrogen from rizhobial fixation [4].

Legume based pastures are an option for producing better quality forage, since the protein content of the sward is improved through the inclusion of legumes with pastures. Also some part of the N fixed by the legume could be transferred to the grass, improving growth, and lowering the necessity for N fertilisation, but in no case fertilisation is suppressed specially P for the legume. [6], states that the productivity of the legume depend on a great extend on the capacity of the legume to fix nitrogen, and although higher quantities are possible, tropical legumes will generally fix 100- 200 kg of N per ha. [8], found that N fixation varied between 30 –280 kg N /ha. This is the case for well fertilised mown pastures. The amount of N2 fixed depend on dry matter yield of the legume hence large amount s of N2 fixation are found with short dry season and long growing season [8]. The extent to which the legume will contribute to the improvement of the pasture will depend on the proportion of legume component in the sward, in general it is said that the legume could represent between 20-50% of the pasture [7].

Reference [6] states that the productivity of legume based pastures could be similar to the productivity of a nitrogen based pasture with 150 kg N /ha/year; under experimental conditions in Puerto Rico yields of 13.67 ton DM /ha/year with a protein content of 7.90% were obtained.

Similar yields (12 ton DM/ha) have been reported by [11] in a mixture of Siratro with grasses. Protein content is reported to be higher under legume-based pastures and depends on the proportion of legume. In swards were the legume component was 50%, the protein contents varied from: 5.4% to 13.2% [9].

5.3 Determination of Scenarios for production, chemical composition

5.3.1 Grasses:

In order to make the estimations about dry matter production and chemical composition three species of grasses were chosen: Napier Grass (*Pennisetum purpureum* K. Schumach.), Guinea Grass (*Panicum maximum* Jacq.), Star grass (*Cynodon* spp). Information on yields and composition during wet and dry season was screened and the average of the chosen values were used as the estimate for further calculations. Some scenarios of production were developed, considering cut interval, fertilisation and irrigation.

Cut interval: It was defined as every 60 days in wet and dry season, hence 3 cuts are carried put during wet season and three cuts are carried out during dry season.
Fertilisation:
Not fertilised
Fertilised: establishment fertilisation: 51 kg N/ha ; 105 kg P_2O_5/ha
maintenance fertilisation: 184 kg N/ha/year ; 52.5 kg P_2O_5/ha
[7]
Irrigation:
Only rainfed (water during rainy season)
Irrigated during dry season (amount of water used has not been established yet)

For the calculations of land required and harvest schedules the information on the scenario of fertilised improved grasslands, during the wet season was chosen (see numbers in bold in table 5-6)

Table 5-6: Dry matter yields per season and per year of improved grasses (averages from three species, see annex).

			Ton DM/ha wet season	Ton DM/ha dry season	Ton DM/ha/year
Improved Grasses	Irrigated	**Fertilised**	**12.8**	**10.3**	**23.1**
		Not fertilised	7.3	5.8	13.1
	Not Irrigated	Fertilised	12.8	3.0	15.8
		Not fertilised	7.3	1.5	8.8
Source: [6, 7, 10, 11]					

Chemical composition of grasses was determined using averages of the three chosen species found in literature (for more details see annex). In the case of well-fertilised and irrigated pastures it is assumed that there is no variation in the chemical composition of the grass, or that is minimal during the dry season, assuming that conditional factors for biomass production could be light and temperature. The data on chemical composition in the dry season could be used for non-irrigated systems of production under rainfed conditions, where water could limit growth and uptake of nutrients.

Table 5-7: Chemical composition of improved grasses in wet season. (average of *Pennisetum purpureum* K. Schumach, *Panicum maximum* Jacq, *Cynodon* spp.)

	Wet season
	%
Dry matter	20.4
	% Dry Matter
Crude protein	8.9
Crude Fibre	33.1
Ashes	12.5
Ether Extracts (and fats)	1.6
Nitrogen Free Extracts	43.9
Source: [11]	

5.3.2 Legumes pure stands

For legume production in pure stands, three species have been chosen: *Desmodium intortum* (Desmodium greenleaf), *Macrotyloma axillare* (Archer), *Macroptilium atropurpureum* (Siratro). Based on expert knowledge of the species that could have better performance under Zambian conditions.

One scenario of production was defined, considering cut interval, fertilisation and irrigation. Cut interval: Every 90 days, in the wet season, hence two cuts in the wet season.

Fertilisation:
Establishment fertilisation: 30 kg N/ha ; 60 kg P_2O_5/ha ; 30 kg K_2O/ha
maintenance fertilisation: 52.5 kg P_2O_5/ha/year, (JO-4)
Irrigation:
Irrigated during dry season

For the calculations of land required and harvest schedules the information on the scenario of fertilised pure legume stands, during the wet season was chosen (see numbers in bold in table 5-8)

Table 5-8: Dry matter yields per season and per year of legumes (averages from three species, see annex).

			Ton DM/ha wet season	Ton DM/ha dry season	Ton DM/ha/year
Legume & Grasses	Irrigated	Fertilised	**11.33**	4.54	15.87
Source: [6, 7, 11] Fredy Baijukya personal communication (Tanzania)					

Chemical composition of legumes was determined using averages of the three chosen species, that were found in literature.

Table 5-9: Chemical composition of legumes in wet season. (average of three *species Desmodium intortum, Macrotyloma axillare, Macroptilium atropurpureum*).

	Wet season
	%
Dry matter	27.10
	% Dry Matter
Crude protein	16.00
Crude Fibre	29.70
Ashes	8.87
Ether Extracts (and fats)	2.30
Nitrogen Free Extracts	45.27
Source: [11]	

5.3.3 Legume & Grass

Star grasses could combine well with *Centrosema* spp. Other possible combinations found in literature include mixtures of Napier grass with *Centrosema pubescens*, *Pueraria phaseoloides*, *Glycine wightii*, *Cajanus cajan*, *Desmodium* spp and *Clitoria* spp, or combinations of Guinea with *Centrosema pubescens*, *Pueraria phaseoloides*, *Desmodium* spp. [11]. Information found in literature refers to mixture of guinea&kudzu (*Pueraria*), and this will be the data used for estimation of yields and chemical composition.
One scenario of production is also defined, considering cut interval, fertilisation and irrigation.

Cut interval: every 60 days in wet and dry season, hence 3 cuts are carried put during wet season and three cuts are carried out during dry season.
Fertilisation:
Fertilised: establishment fertilisation: 30 kg N/ha ; 60 kg P_2O_5/ha ; 30 kg K_2O /ha
maintenance fertilisation: 52.5 kg P_2O_5/ha/year
[7].

For the calculations of land required and harvest schedules the information on the scenario of fertilised legume grass combination, during the wet season was chosen (see numbers in bold in table 5-10)

Table 5-10: Dry matter yields per season and per year of legume & grass pastures (Napier-kudzu mixture)

			Ton DM/ha wet season	Ton DM/ha dry season	Ton DM/ha/year
Legume	Irrigated dry season	Fertilised	**8.27**	5.4	13.67
Source: [6]					

Table 5-11: Chemical composition of legumes & grass pastures in wet season.

	Wet season
	%
Dry matter	21.0
	% Dry Matter
Crude protein	12.0
Crude Fibre	36.3
Ashes	9.0
Ether Extracts (and fats)	2.8
Nitrogen Free Extracts	39.7
Source: [9, 11]	

5.4 Costs of production of green material

Estimation of costs of production of 1 ton of green material on a dry matter basis, was done using as the main costs fertiliser and labour inputs, land has not been included in the costs of production. Prices for fertilisers were obtained from internet sources for the most common fertilisers used in the area. In this case: Ammonium nitrate (34% N, 0% P_2O_5, 0% K_2O), Single super Phosphate (0%N, 21% P_2O_5, 0% K_2O) and compound D (10% N, 20% P_2O_5, 10% K_2O). Labour inputs were estimated through expert knowledge.

Table 5-12: Costs of production of green biomass (Euro/ ton DM/ wet season)

Green material	Cost Euro/ ton DM/ wet season
Rangelands	21.5
Improved grasslands	29.1
Legumes pure stands	21.3
Legume & Grass pastures	27.4

5.5 Harvest Schedule

The first year of the legume crop is the year of establishment, in this year it is not recommended to harvest the legumes intensively but to let them grow. Moreover, the yields during this first year are low. Once the legume is established the normal harvest of the legumes could be carried out. With expert knowledge it was determined that legumes could be cut every 90 days (three months). Considering a rainy season of six months there will be two cuts per field, per season.

The harvest schedule of the legume is done considering work for seven days a week, to keep the process running without stop during the rainy season. The area to be harvested per day will be 4,5 ha which will supply 94.1 ton of fresh material per day, to be processed. Given the small area to be harvested per day and provided that availability of machinery in Zambia is low, it is assumed that the harvest will be carried out by hand. The harvest of the 4.5 ha will be divided in two shifts of 6 hours each; From expert knowledge it was determined that 15 men could be required to harvest 1 ha of grass in 1 day of 8 hours. Based in these figures, 45 men are needed for each shift of six hours, giving a total labour requirement of 90 people per day. A summary of the figures used for determining requirements of labour and costs of harvesting could be seen in table 5-13.

Table 5-13. Figures on harvest process

Figure	Value	Unit
# cuts day	1.0	cut
# cut/field/season	2.0	cut/field/season
# cut in 6 months	180.0	cuts
# fields	90.0	fields
yield/ cut	5.7	ton DM/ha
yield/ cut	20.9	ton FM/ha
green material needed/day	94.1	ton FM/day
area to be harvested	4.5	ha/day
# shifts	2.0	shift
area to be harvested/shift	2.3	ha/shift 6 hour person
Harvest menday/ha needed	15.0	men/ha
ha/menday	0.0667	ha/men
ha/hour	0.0083	ha/hour * men
area/shift 6 hours	0.05	ha/shift 6 hour person
Persons needed per shift 6 hours	45.0	men/shift
Persons needed per day	90.0	men/day
payment/person/day 8 hours	1.5	euros
payment/person/hour	0.2	euros
payment/ shift/person	1.1	euros
payment total/day	101.3	euros
payment total/season	18,233.3	euros

6. Process Structure

6.1 Criteria and selection

This chapter will explain how all information from the foregoing chapters is used to assess the various design criteria. Some of the criteria, that determine the choice of design are, for example, productivity, environment, safety and cost, etc.

6.1.1 Storage facilities (T01-T05)

There are several storage facilities in the design. A water buffer storage tank is desirable to store the reused water, which provides water needed for the cell disruption stages. The size of the tank depends on the amount of process water, or the productivity of the process. For safety reasons, to reduce the bleed potential, liquid level in the tank has to be determined. Capacity of storage facilities for raw material (grass), product (protein cake), intermediate (fiber, gas from gasifier) and by-products (ash, fibre) depends on the productivity of the plant and the material conditions. Detailed design and selection is referred to chapter 8. Therefore, productivity, safety and material condition criteria are used to design the storage tank.

6.1.2 Heat Exchanger (E02, E03)

Two heat exchangers are used in the process. Heat exchanger E03 is used to preheat air before it enters the gasifier. E02 is used to cool process water down to 30°C for environmental reasons. The requirement of productivity and chemical phases of hot and cold streams that determine heat exchange coefficient are taken into account for the design. Hence the choice of heat exchanger is determined by material condition and productivity criteria.

6.1.3 Cell disruption process (T01, X01-X06, V01, V02, A01, S01)

This process comprises two steps, cell disruption and solid (fiber) /liquid (protein, sugar, other components solution) separation. Grass falls into a hopper with outlet control to ensure a constant flow rate of grass into the washing section through an elevator, and then transported by the conveyer belt to the hopper placed above the disc refiner. There are two washing stages. One is to submerge the grass in water under the belt. A water sprayer is placed above the second belt. The hopper above the disc refiner also has an output control to keep a steady stream of grass enters the disc refiner. A balance is used to weigh the grass input to the disc refiner before it goes into the process. Design of the hoppers and disc refiner is based on the flow rate and cost, and for disc refiner selection is also related to the cell disruption efficiency. Equipment design elements are determined by the productivity, cost, and efficiency (equivalent to the reaction conversion in a chemical term) criteria.

The choice of equipment in solid/liquid separation depends on the concentration of solids, the feed rate and the size of solid particles. Considering the total energy and equipment cost, combination of a rotary drum filter and a belt dryer is the best choice. In this section, design criteria are material conditions of input and output streams, energy consumption, productivity and economics.

6.1.4 Protein separation process (E01, X05)

Evaporator (E01) is used to concentrate the protein/sugar solution, which finally comes out of the plant as protein cake. A large amount of water needs to be removed from the solution, multi-effect evaporator systems and single stage evaporator are compared in the design (Chapter 8) for the sake of minimization of heat consumption and costs for the system. Selection of the most suitable evaporator type for a particular application depends strongly on the throughput required and feed conditions; especially in our case proteins are very heat sensitive. Evaporator choice is determined by the economic, productivity and material condition criteria.

Belt dryer (X05) follows the evaporator to remove the remaining water because there is still too much water in the protein cakes. A rotary drum filter and a belt dryer are compared in the design but it was concluded that the costs of the filter are very high and the protein particles were very small. A belt dryer is more suitable. Thus, it is determined by the criteria of economic and productivity.

6.1.5 Gasification process (T02, X07,R01, S02, S03, K03,03, R02)

The fibers from the fiber-protein separation step will be converted into electricity, which is used to run the whole process. A gasification process is chosen because of the small system capacity with reasonable efficiency, low investment costs, good reliability, and simple operation. Elevator (X07) transports the fiber cakes into the gasifier. The fiber cakes are fed to the gasifier at the top. The gasifier (R01) is a system, which converts biomass or other carbon sources into combustible gas ('producer gas') using thermal processes such as pyrolysis. Biomass is combusted imperfectly by way of controlling the flow of air or steam into the gasifier to convert the solid energy carrier into a gaseous one, generating a combustible gas, which consists mainly of H_2, CO, CH_4, CO_2 and C_nH_m. After cleaning, in S02 and S03, the gas is stored in T03 to allow continuous operation, and then fed into the engine mixed with air and combusted to generate electricity. Considering the scale of electricity generation, a gas engine (R02) is chosen. In this process, any carbon containing waste can be converted into electrical energy, turning waste into (valuable) resources with relativity low emissions. In this process, createria of productivity, investment cost, reliability and environmental friendly are considered to determine the proper process.

6.1.6 Pumps and blowers chosen (P01-P09, kK01-K04)

Several pumps or blowers are used in the plant either to transport liquid or gas through the process. Because the amount of liquid or gas only depends on the requirement of productivity and there is no higher pressure or vacuum operation in the process, the choice of pumps and blowers for transportation is determined only by productivity criteria

6.1.7 Utility chosen

After considering the cost of different utilities and required amount of heat transfer in the plant (calculation is based on plant productivity criteria), utilities are chosen as the use of steam or water generated in the process to make a close cycle and without any extra investment on it (refer to chapter 8). Therefore, the utilities selection here is determined by productivity criteria and cost criteria.

6.2 Process flow scheme

The process flow sheet can be found in appendix 3.

6.3 Time shift

The process proposed in this report consists of rather simple units. The complexity lies in the way the different units have to be optimized.

Daily events during production (wet season).
In appendix 7, the different events in a typical day of operation are shown. These events are described below in brief.

Harvesting – 6:00-18:00
Since the harvesting of the grass is done outside, it is limited by the availability of light. Harvesting will be done from dawn until dusk.

Grass storage – 6:30-22:45
A first, small load of grass arrives at 6:30, so that refining can start. From then on, grass is added during the course of the harvesting day

Grass refining – 7:00-23:00

Gasification - continuous
The gasifier will be operated continuously throughout the active part of the year. Due to the high daily gas-requirement of the process, it will run at a rate of ~330 kg fibre/hour.

Evaporation and drying - continuous
The removal of water from both the fibre and protein fractions is done continuously during the active part of the year, barring short periods of downtime for cleaning and maintenance purposes.

Power generations – semi-continuous
Electricity is produced throughout the day, but during disc refiner operation the power demand significantly increases. Two separate sets of engines are to be used: a 400kW block to power the plant during peak performance, and a 60kW block to power the rest of the plant and farm.

Storage
The disc refiner operates for only 16 hours per day, while gasification and evaporation will be done continuously. This means that intermediate storage is required. During refining, gas is consumed, while fibre and protein/sugar-water are produced. The continuously operating parts of the plant respectively replenish and process these resources.

Right before the start-up of the disc refiner, the gas storage tank is completely filled, and the other two tanks are at their minimum occupation. As the disc refiner starts, the engine consumes gas, and the gas tank is slowly emptied (the engine consumption rate is higher than the gasifier production rate). As the disc refiner starts producing fibre and protein/sugar-water, the respective storage tanks slowly fill up. When the disc refiner is shut down, the gas tank slowly fills up again, and the other two tanks are slowly drained.

The different parts of the process require some maintenance throughout the year, which mainly poses a problem for continuously operating units. This maintenance doesn't necessarily take place at the same time for all process parts. To ensure that downtime of a piece of equipment doesn't affect the rest of the process, all storage tanks will be kept at additional capacity.

Dry season
During the dry season, most activities of the wet season cease. Slight alterations occur in the use of the gasifier. The protein cake and fibre stores are slowly depleted.

The gasifier can run on a full gas-tank for 35 hours. This means that one could run the gasifier at full rate to fill the tank, and then shut down the gasifier and run on stored gas only. This sort of technique could be used to create downtime to perform maintenance on the gasifier. Initially the aim was to use this to have the gasifier only run for a day every few weeks, but the required volume to store gas is too large. Instead the gasifier will be run at 20% capacity, corresponding to the gas-requirement of the engine

6.4 Process stream summary

The in- and outgoing streams are defined in table 6-1 and 6-2.

Table 6-1: Process streams going into the battery Limits

Ingoing Streams

STREAM Nr.	:	101,102		304	
Name :		grass feed		air in	
COMP		ton/a	kg/s	ton/a	kg/s
Water					
grass		1.62E+04			
Ash					
Protein					
Sugar					
Fibre					
O2				7.04E+03	
N2				2.32E+04	
CO					
CO2				1.38E+01	
CH4					
H2					
Total flow	ton/a	1.62E+04	1.04E+00	3.02E+04	1.94E+00
Enthalpy	kw	0.00		0.00E+00	
phase	L/V/S	S		G	
Press.	bara	1		1	
Temp	oC	25		25	

Figure 6-2: Process streams going out the battery Limits

Outgoing Streams

205		309		321		323		324		403,404		506		507	
protein cake		fibre out		cartridge ash		ash out		engine exhaust		wastewater		protein dryer exhaust		fibre dryer exhaust	
ton/a	kg/s	ton/a	kg/s	ton/a	kg/s	ton/a	kg/s	ton/a		ton/a	kg/s	ton/a	kg/s	ton/a	kg/s
1.34E+02		1.43E+01						6.41E+03		7.47E+03		1.26E+03		2.64E+03	
0.00E+00		4.51E+01													
3.47E+02		1.24E+00		4.01E+00		8.09E+01		4.05E-02							
5.63E+02		2.00E+00													
1.63E+03		5.81E+00													
0.00E+00		7.44E+01													
								4.26E+02							
								2.31E+04							
								1.74E+03							
2.68E+03	1.72E-01	1.43E+02	9.18E-03	4.01E+00	2.58E-04	8.09E+01	5.20E-03	3.17E+04		7.47E+03	4.80E-01	1.26E+03	8.09E-02	2.64E+03	1.70E-01
22.73		0.00E+00		0.01		0.16		72.99		1.00E+01		186.43		401.13	
S		S		S		S		G		L		V		V	
1		1		1		1		1		1		1		1	
70		25		40		40		55		30		50		80	

The detailed mass and heat balances can be found in appendix 4.

6.5 Utilities

6.5.1 Utilities requirement

Cold utility:
Two options, CW (cooling water) and CA (cooling air) are available as cold utility. CW is chosen as cold utility for condenser E02 to cool water from 50^{0}C to 30^{0}C. For cooling water the heat capacity (4.18 kJ/kg K) and heat film coefficient (0.20) of water are higher than that of air (1.00 kJ/kg K and 0.10 respectively). It means that less amount of cooling water needed to achieve the same effect as air and the area needed is much less. It is the reason why CW is chosen as cold utility in this process.

Hot utility:
Evaporator E01 needs LP steam (1 bar, 100^{0}C), which is produced from the process itself. A furnace is used to heat part of recycled water to steam at 100^{0}C. Therefore, steam doesn't have to be bought. Because this process is designed to be suitable for Zambia countryside, using the steam from process itself is more convenient and reduce investment.
Producer gas (661^{0}C) is used for belt dryers (X05 and X06) to supply the heat. Steam and hot air could be the options. However, considering the economic and heat integration, using hot producer gas is the best option.

Electricity utility:
All the electricity (450kW) needed for the process and farm daily usage is produced by process itself.

Table 6-3: The requirements of utilities

Utility	Unit	Total requirment
Electricity	kWh/a	5.01 E06
Steam	Ton/a	3.59E04
Cooling water	Ton/a	4.63E04

From table 6-3, it is found that electricity power is the major utility. (Details in appendix 5-9) Because cooling water, steam, producer gas and electricity are all produced by the process itself, they are not bought (are inside the boundaries).

6.6 Process yields

Table 6-4 The process yield (excluding the utilities)

Name	Stream	t/a		t/t product	
	No.	IN	OUT	IN	OUT
AIR	304	2.27E+03	0	8.47E-01	0
GRASS	101	1.62E+04	0	6.04E+00	0
VAPOR	506/507	0	3.90E+03	0	1.46E+00
EXHAUST GAS	324	0	3.17E+04	0	1.18E+01
ASH	312/323	0	1.39E+02	0	5.18E-02
PROTEIN CAKE	205	0	2.68E+03	0	1
FIBER	309	1.10E+03	1.43E+02	4.11E-01	5.34E-02
WASTE WATER	404	0	7.47E+03	0	2.79E+00
Total	--	1.95E+04	46011.18319	7.30E+00	1.72E+01

7. Mass and Heat balances

Three types of balances will be discussed: Nutrient balances, to ensure sustainability, and mass and heat balances. The main use for balances is to check whether any errors have been made along the design, and to see where those errors can be found. First the mass balances, and then the heat balances will be discussed. Overall balances will be discussed in slightly further detail than the local balances. See also appendix 4 for the stream summaries and balances.

7.1 Nutrient Balances

This nutrient balance has been created as a tool to assess the impacts of the production of legumes for protein cake production on the nutrient status of soil. Many processes govern the transfer of nutrients in the soil-plant-animal system, and there is extensive information on nutrient cycling in different production systems. Nevertheless, the balance presented here is a partial balance, which considers the main fluxes in order of magnitude (inputs and outputs of the system).

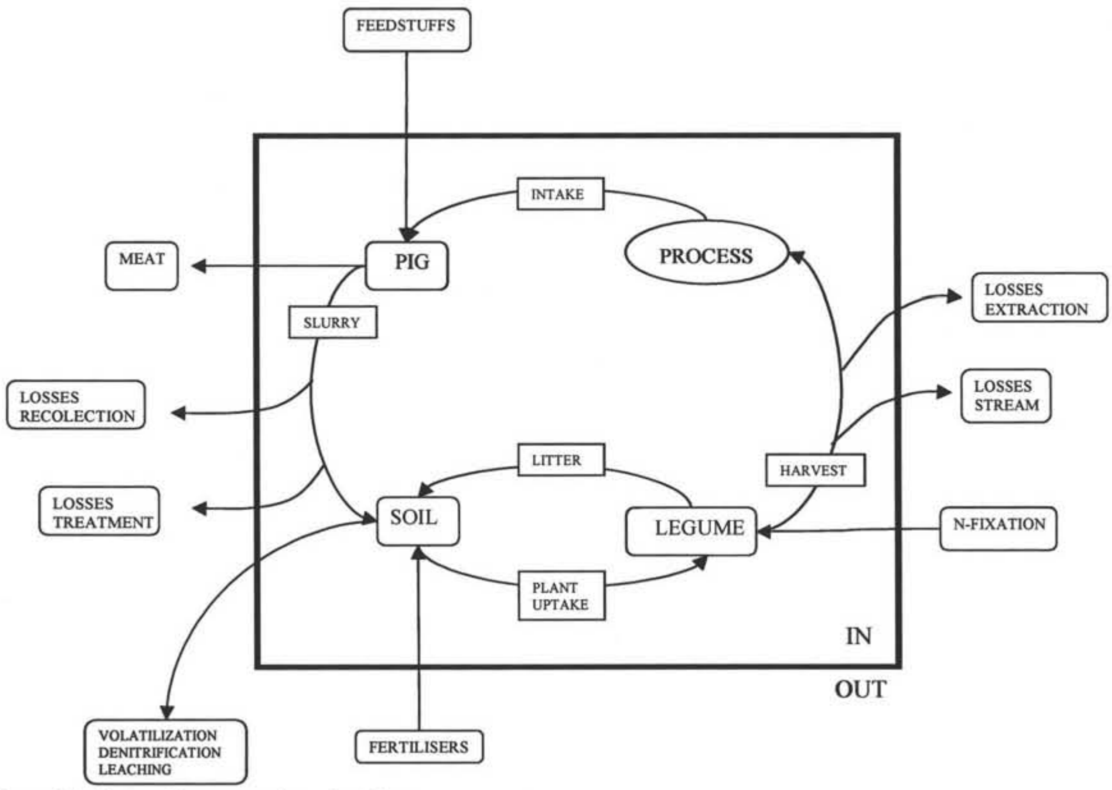

Figure 6-1: System diagram and nutrient flows

7.1.1 Boundaries of the system, and processes included

The complex formed by soil, legume, animal, and the process is defined to be within the system boundaries.

Hence, all the transfers that occur from the soils to the legume, legume to the pig, pig to the soil, are internal fluxes of the system. All the fluxes which leave the system are considered as losses, in this case the amount of nutrients that is retained in the body mass of the pig (meat), losses determined by the efficiency of the process in the transformation of green matter to protein cakes, namely the losses in the stream and losses in extraction step. Besides the former, there are losses of nutrients during storage and treatment of manure before the application on the field.

The inputs of the system are the Nitrogen fixed by the legume, fertilisers added to the soil and other feedstuffs that are used to feed the pigs. Nutrients considered are N, P and K on a yearly basis, expressed in kg/ha. For the sake of simplicity processes in the soil that lead to losses (erosion, nitrificaiton, denitrification, leaching, ammonia volatilisation) and inputs like deposition and processes of inmobilisation have not been considered in the balances. Rates of mineralisation have not been accounted, to estimate the release of organic N from soil organic matter and pig manure. All the processes listed above determine nutrient availability for the plant, specifically for N which is the most susceptible element to transformation in the soil [1]. Hence the balance presented give us an indication of the total contribution of N,P and K to the soil but the amount of these nutrients available in the soil is less than that calculated. Losses in the soils will depend to a great extent on soil characteristics, environmental conditions and methods of application of the slurry and fertiliser. These factors could make values of nutrient losses governed by these processes highly site specific.

7.1.2 Legume, animal & soil relation

The values for dry matter production and composition have been taken for legumes in pure stands, (see chapter raw materials). Values of N fixation for the legumes planted for green biomass production are in the range of 45 to 55% in pure stands [2]. Nevertheless, [3] point out that N-fixation by legumes could reach up to 90% from the total N in the plant, specifically combination of grass and legumes, due to the strong competition of the grass for soil N which makes the legume rely on atmospheric N. For balance calculations both scenarios have been considered. Plant uptake has been calculated as the difference between the total amount of N in the plant and N supplied by N-fixation. Since the legume is subject to harvest by cutting during the wet season, it is assumed that during this season the contribution of nutrients from litter fall is nil. Nevertheless for the dry season it is assumed that 30% of the biomass produced will be returned to the soil. Calculations of decomposition and mineralisation of these residues have not been included, the assumption is that the nutrients from litter fall are available in the first year.

The nutrient requirements of pigs, the number of animals, the efficiency on recovery of protein in the first stream (85%) and the efficiency of extraction of protein from this stream (95%) have defined the area needed and the amount of grass harvested and processed. Once the green material is harvested it is processed for extracting protein. The efficiencies of extraction have been used to calculate the amounts of nutrients (N, P, K) that are given to the pigs. The intake of N equals the amount of protein content divided by 6.25, the intakes of P and K have been obtained from literature. The amount of P supplied by the protein cakes is less than the amount in the intake; the difference could be supplied from other feedstuffs. For this reason, a flow of nutrients from outside (feedstuffs) has been considered in the nutrient balances. For K, the amount supplied by the protein cakes exceeds the amount given by literature in the intake; for sake of simplicity this extra amount has been added to the intake. The calculation of the amount of nutrients that goes to the faeces has been determined as the difference between the intake and the retention of nutrients in the body.

Losses during recollection and treatment of the manure have been considered assuming that faeces and urine are mixed and recollected (slurry), and that they are subject to aerobic treatment. These losses are especially large for N.

The balance is determined by the difference of the main inputs minus the outputs (see table 7-1 and 7-2). The parameters used for the calculation of balances are available in table A4-1 in appendix 4-3.

Results of the calculations reveal that under the actual assumptions of production and management, the balances are negative for N (-64.17 kg/ha/year), positive for P (28.40 kg/ha/year) and negative for K (-44.72 kg/ha/year) when N fixation is considered to be 50% of total N in the plant. When N fixation is assumed to be 90%, the balances present a surplus scenario, N (51.85 kg/ha/year), P (28.40 kg/ha/year) and K (-44.72 kg/ha/year). N fixation is the key factor to determine the result of the balance. In the case of P there is a positive due to the addition of P through fertilisers and even more important the contributions of other feedstuffs included in the pig feed. K has a negative value in either case (50 or 90% fixation) since no additions of fertiliser for this element were considered in the recommendations of fertilisation found in literature. In this case the use of fertilisers is recommended.

N content of pig manure is high and susceptible to losses, with the greatest losses of N occur in the recollection and treatment of manure, and during the first phase of extraction of protein in the process. In this case, one scenario of production and treatment of manure was explored. Nevertheless other options for storage and treatment of manure could be explored to determine the possibilities of diminishing losses.

Table 7-1: Nutrient Balances when N-fixation is 50% of total N in the plant.

	N	P	K
Flows	kg./ha	kg./ha	kg./ha
Soil Stocks	1650	60	2932.5
Inputs			
Fertilisers	0	22.9	0
N fixation	145.0	0.0	0.0
Feedstock	0.0	68.4	0.0
litter turnover dry season	34.8	2.3	10.3
Total Inputs	**179.81**	**93.69**	**10.26**
Outputs			
Intake losses	0.0	0.0	0.0
Losses stream	43.5	2.9	12.8
Losses recovery efficiency	12.3	0.8	3.6
retention (meat)	91.0	19.4	7.2
losses in recollection	47.3	0.0	14.8
Losses slurry treatment	49.90	42.16	16.46
Total Outputs	**244.0**	**65.3**	**55.0**
Input –Outputs	**-64.17**	**28.40**	**-44.72**

Table 7-2: Nutrient Balances when N-fixation is 90% of total N in the plant.

Flows	N	P	K
	kg./ha		
Soil Stocks	1650	60	2932.5
Inputs			
Fertilisers	0	22.9	0
N fixation	261.0	0.0	0.0
Feedstock	0.0	68.4	0.0
Litter turnover dry season	34.8	2.3	10.3
Total Inputs	**295.83**	**93.69**	**10.26**
Outputs			
Intake losses	0.0	0.0	0.0
Losses stream	43.5	2.9	12.8
Losses recovery efficiency	12.3	0.8	3.6
Retention (meat)	91.0	19.4	7.2
Losses in recollection	47.3	0.0	14.8
Losses slurry treatment	49.90	42.16	16.46
Total Outputs	**244.0**	**65.3**	**55.0**
Input -Outputs	**51.85**	**28.40**	**-44.72**

7.2 Mass balances

7.2.1 Overall balance

Total mass entering the system equals the total mass leaving it. All streams entering are streams nr. 101, 304 and 307, while all streams leaving are stream nr. 205, 309, 312, 323, 324, 325, 404, 506 and 507. Their balance summary is given in table 7-3.

Table 7-3: Stream summary, the in- and outgoing flows

STREAM Nr. :	101,304,307 all N	205,309,310,312,323, 324,404,506,507 all OUT	all N - all OUT
COMP	ton/a	ton/a	ton/a
Water		1.80E+04	-1.80E+04
grass	1.62E+04	1.55E+02	1.60E+04
Ash		4.90E+02	-4.90E+02
Protein		5.70E+02	-5.70E+02
Sugar		1.65E+03	-1.65E+03
Fibre		2.56E+02	-2.56E+02
O2	7.04E+03	4.26E 2	6.61E3
N2	2.32E+04	2.31E 4	3.67E1
CO2	1.38E 1	1.74E+03	-1.72E3
Total flow ton/a	4.64E+04	4.64E+04	0.00E+00

As can be seen, the balances fit, the summed incoming and outgoing streams being equal.

7.2.2 Local balances

Throughout the project, local balances have been successfully used to check the correctness of the unit designs. They can also be applied to further check the consistency of the current design. There is always a possibility that the overall mass balance closes even if there are errors in the unit designs. Even though it is unlikely that those errors cancel each other out completely, local balances should be used to check the correctness. The process will be split into three parts, which will be checked for consistency. These three parts are grass processing (101 up to 302 and 201), protein production (201 and onward) and fibre processing (302 and onward).

Grass processing
Incoming streams: 101, 410
Outgoing streams: 201, 302, 403, 507

Table 7-4: Grass processing

STREAM Nr. :	101 410 all in	201 302 403 507 all out	 all in - all out
COMP			
Water	3.15E+04	4.32E+04	-1.17E+04
grass	1.62E+04	6.66E+02	1.55E+04
Ash		3.65E+02	-3.65E+02
Protein		5.92E+02	-5.92E+02
Sugar		1.72E+03	-1.72E+03
Fibre		1.10E+03	-1.10E+03
Total flow ton/a	4.76E+04	4.76E+04	0.00E+00

Protein production
Incoming streams: 201
Outgoing streams: 205, 410, 506

Table 7-5: Protein Production

STREAM Nr. :	201 all in	205 410 506 all out	 all in - all out
COMP			
Water	3.29E+04	3.29E+04	0
grass			
Ash	3.47E+02	3.47E+02	0
Protein	5.63E+02	5.63E+02	0
Sugar	1.63E+03	1.63E+03	0
Total flow ton/a	3.54E+04	3.54E+04	0.00E+00

Fibre processing
Incoming streams: 302, 304, 307
Outgoing streams: 309, 310, 312, 323, 324

Table 7-6: Fibre processing

STREAM Nr. :	302+304+307 all in	309+310+312+323+324 all out	all in - all out
COMP			
Water	2.11E+02	6.45E+03	-6.24E+03
grass	6.66E+02	1.55E+02	5.11E+02
Ash	1.83E+01	1.43E+02	-1.25E+02
Protein	2.96E+01	6.90E+00	2.27E+01
Sugar	8.59E+01	2.00E+01	6.59E+01
Fibre	1.10E+03	2.56E+02	8.43E+02
O2	7.04E+03	4.26E+02	6.61E+03
N2	2.32E+04	2.31E+04	3.67E+01
CO2	1.38E+01	1.74E+03	-1.72E+03
Total flow ton/a	3.23E+04	3.23E+04	0.00E+00

These separate parts are also consistent.

7.3 Heat balances

Just as with mass, no heat can be lost. Heat balances have been used to check the individual units for consistency, and have been applied on both total flow scheme and local sub-systems. It quickly became clear that something was wrong, as the total stream balance was off by 693kW, while something around 227kW (water losses and cooling water) was expected. After a quick search, it became apparent that a unit error occurred in the fibre drying section; 2.26kJ/kg instead of $2.26 \cdot 10^3$kJ/kg was used. This difference results in a heat duty changing from 1.85kW including losses to 408kW excluding losses (which are quantitatively added and removed, and as such only influence the actual heat duty of the evaporator).
693kW - 408kW - 227kW = 58kW, 5% of the total heat input of 1280+788. This difference still is unacceptably large, but can be explained to follow from cascading of errors: during closing of recycles, streams change marginally (<1%), which can result in over or under sizing of equipment, resulting in too large or too small duties, which in turn are used in heat integration, which gives different values for the required additional heat. Fixing this requires iteration of the different equipments, which was nearly impossible in the timeframe available after discovery of the error. Instead, since the process is unfeasible even if this error results in a 50% reduction of overall plant cost (rather than the more likely 2-3% *increase*), focus was moved to finding alternatives for grass-refining and pig feeding.

8. Process and Equipment Design

8.1 Cell crushing

8.1.1 Grass storage (T02)

Once the grass is cut in the field, it must be stored. The largest amount of grass that needs to be stored is the amount present when the field workers stop working, but the process is still working. The field workers stop at 18:00, but the process keeps running till 23:00. Thus, the storage facility needs to be able to store grass for 5 hours of processing. Since the grass flow rate is 5.6 ton per hour (see mass balances) when the refining machine is on, the storage facility needs to be able to hold at least 30 tonnes of grass. The grass must be washed after it is stored and will get wet anyway. Therefore it is not needed to protect the grass from the rain, so the storage does not necessarily need a roof.

The bottom of the storage bunker is preferably wood. If pieces of the wood get loose and come into the process, they are broken in the disc refiner, just like the grass. If the floor would be of concrete and large enough pieces get loose, they act just like sand in the disc refiner. This could destroy the discs.

The bunker does need walls. There always is wind in Zambia, especially in the rain season [1], when it can be stormy from time to time. The walls protect the grass from being blown away. This wind can also transport sand, which can destroy the discs in the disk refiner, so although a roof is not needed against the rain, it is against the wind. Again to protect the disks from sand, it is best to use wood instead of concrete.

It is assumed that stored grass consists for 50% grass, and the other 50% is air. Since the largest part of grass cells is water, the density for grass cells is assumed to be 1.0 ton/m^3. Neglecting the density of air (which is less than 1% than the one from water), the density of the stored grass is 0.50 ton per m^3. With this the 30 tonnes of grass occupy 60 m^3. People must be able to walk in the bunker, but it sould also be easy to take the grass out, so a height of 2 meters is chosen. In that case a floor of 6 by 6 meters is enough to store all the grass.

Since both storing the grass that comes from the field, and taking out the grass that goes to the process happen continuously, 2 entrances are needed for the bunker. On 1 side of the bunker an opening is needed for people to put the grass that they have collected from the field, on the other side a conveyer belt over the whole length must be placed which transports the grass towards the washing section of the process.

The price for the grass storage is assumed to be € 15,200 [2].

8.1.2 Grass washing (X01 - X03 and V01)

The grass falls from the conveyer belt into a hopper with outlet control to ensure a constant flow rate of grass into the washing section.

In the wood industry sand removal is easy. The wood is submerged and because of the low density the wood floats up again while the sand is collected in the bottom. But legumes are not woody since 73% of the mass of legumes is water. Because of that the density of grass is around the same as that of water. It can be compared with leafs falling in a pond. As long as they are on top of the water they float, but once the get totally submerged they will go down until they hit the bottom. This means that a different kind of washing must be used for this process.

The first step in washing is a conveyer belt submerged in water. The conveyer belt must be made from either stainless steel or a very tough plastic to withstand the forces applied to it combined with the constant water contact. This belt also needs holes of a few millimetres in it, to make sure the sand can fall through, but the legumes cannot. The belt moves with shaking movement through the water to let sand from legumes on the top fall through the other legumes until it reaches the conveyer belt.

On the site of Integrated Publishing [3] the maximum speed of a conveyer belt was found to be around 100 meters per minute, with a loading capacity of 300 ton per hour. These values may not be exceeded.

By lack of better data for conveyer belts used for grass, information has been used from a sand transporting company [4]. Since sand is heavier than grass, a conveyer belt that can transport sand must also be able to transport grass. A conveyer belt of 1 meter wide and 2 meters long uses a motor of 2.2 kW. From now on, all conveyer belts will be assumed to be 1 meter in width.

The retention time of the grass is set as one minute. With the given amount of grass throughput of 5.6 ton per hour this means that 94 kg grass should be in the washing machine at any given time.

First the grass is transported from the storage tank to a hopper. This is done with an elevator belt (X01). The washing machine will be 1 meter high and the hopper is around 3 meters high. The grass is transported over a height of 4 meters. With an angle of 30^0, the length of the belt will be 8 meters.

The hopper (V01) should give a constant throughput to the first washing stage. For a normal situation, the hopper should be big enough to store grass for one minute. In case something goes wrong with the washing stage, the hopper must be able to close but the supply of grass is still going on. Assuming that repairing the belt costs 15 minutes, then the grass must be stored for 15 minutes. With a throughput of 5.6 tons of grass per hour and a density of grass of 500 kg per m^3, this will give a hopper with a volume of 3 m^3. The height will be 3 meters.

In order to properly wash the sand in the submerged washing station, no more than 5 cm of grass can be stacked. Again it is assumed that only 50% of the volume of the grass flow is grass cells. This gives a volumetric flow rate of grass cells of 0.187 m^3 per minute (appendix 5-2, table A5-5). With the assumptions of 5 cm grass height and a belt width of 1 meter, this gives a belt speed of 3.75 meters per minute (appendix 5-2, table A5-6). Since the residence time of the belt was set at 1 minute, the length of the first washing unit (X02) must be 3.75 meters long and 1 meter wide. The unit must be around 1 meter high, in order to have enough space to collect all the sand. Every night when the machines are not working, the sand can be removed from the bottom.

At the end of the 1st washing step, the grass is taken out of the water and put on another belt (X03). This belt is the second washing step. Here the grass is sprayed with water in order to get the last of the sand out. The third belt must also be able to withstand the combination of mechanical force (because of the shaking) and water, in combination with the small holes for the sand to fall through. Under the belt a collection bunker is needed to get the water and sand together. The water used for spraying comes from the condensed steam, used in the protein concentration steps. All the water that is produced there is sprayed over the grass; the amount of water is 31.8 kg per minute. The water mass flow needs to be at least half of the mass flow of water in order to get ample cleaning. If this mass flow would become more than 2 times the mass flow of grass, all excess water will be purged. Using more than that amount of water is not likely to clean more, but will cost more in investment of sprayers.

Once again a residence time of 1 minute is chosen. In order to make sure all the sand is washed out, the height of grass must be halved. Having the washing belt of the second step run at double speed can do this, but since the speed is doubled, also the length of the second washing step also must be doubled. This gives a length of 7.5 meters (appendix 5-2, table A5-7). The width of the unit is 1 meter. The height is not really important, but the spray column should not be more than 20 cm above the grass.

This water with a very low concentration of sand is collected at the bottom and pumped out of the process to be transported to the fields.

After these two washing steps the legumes are ready for cell breaking. It is assumed that 5w% watr sticks to the cells. So this means that together with the 5.6 tons of grass per hour 0.28 ton of water enters the cell disruption step.

The prices for the different equipments are listed in table 8-1.

Table 8-1: Prices for equipment

Apparatus	Specification	Price [€]	Reference
X01	4 m height	34,000	[7]
X02	3.75 m length	8,500	[25]
X03	7.5 m length	16,900	[25]
V01	3 m^3	4,000	[29]

8.1.3 Cell disruption (V02, X04 and A01)

An elevator (X04) transports the legumes into a hopper (V02) placed above the disc refiner. This hopper has an output control to ensure a steady supply of grass for the disc refiner.

The hopper will be of the same size as the other one, because the flow through the hoppers is the same. The dead time for the disk refiner is also assumed to be 15 minutes. If it takes more time to repair the disk refiner, there is enough time to stop the rest of the process.

The disk refiner is around 2.5 meters high, so together with the 3 meters high hopper, the elevator needs to be 5 meters high. With a slope of 30^0 the belt is 10 meters long. The price for this elevator will be € 36,700 [7].

Inside the disc refiner (A01) a screw transports the grass towards the disc [5,6]. The legumes are mixed with water at the entrance of the disc refiner. This mixing is 1:1 on grass cell mass basis; the water must be added to be sure the screw inside the disc refiner can transport the legumes in a steady stream towards the discs. A second function of the water is cooling. The breaking of cells is based on friction, so heat will be formed. In the wood industry water is added until the dry matter content is around 33% maximal. Since grass is not as tough as wood, less friction heat will be produced, so less water is needed. The ratio of 1:1 is chosen because it is then still possible to have a liquid flow after the cells have been broken.

A disc refiner is used to inflict enough shear force on the grass cells in order to break them. According to the first information from the principals [8] 90% disruption is possible, but in the patent [9] 85% is reached with a disc refiner. Thus, the disruption efficiency used in this process is 85%. Disc refiners are bought according to their dry matter throughput. Of the 5.6 ton of grass per hour that must be processed, 27.6% is dry matter, which is 1.52 ton per hour. Together with the 16 work hours per day, this gives a total dry matter throughput per day of 24.3 ton.

The grass processing plant in the Netherlands consumes 100-150 kWh [mail from Mr. Sanders] per ton of dry matter. It is assumed that the grass cells in the Netherlands have the same strength as the legume cells in Zambia, so the power needed for the 1.52 tonnes dry matter per hour is 228 kW. This electricity will be provided by the gasification. From information from the U.S. Department of Energy [10], the efficiency of a 228 kW engine is 92%. This means that 92% of the electric input is used for movement, and the rest is converted to heat. For the process this means that 18 kW of heat is formed, which will heat the air around the motor. Since this motor needs to be inside and the temperature in Zambia is around 25 degrees Celsius [1] good ventilation and cooling pins are needed to make sure it gets not too hot inside.

According to reference [11] 20 to 33 percent of the energy input is used to disrupt the fibres in wood. The harder the wood, the lower the percentage of energy used for disruption and the more heat is produced. It is assumed that grass can be compared to soft wood, and as such will have around 33% used for cell breaking. This results in a temperature rise of 10 °C in the stream (appendix 5-2, table A5-8).

On the Internet a second hand disc refiner was found [12]. For the first farm this machine could be used. But for proper calculations prices of new machines should be considered. Based on that machine, assumptions are made for the price of a new machine. This machine can handle 40 ton dry weight per day, the double of what we need. The motor is 300 HP, which is 224 kW, so the same as needed. The price for this second hand unit is €35,000. Since our throughput is half, the size of the disc is smaller, and the costs for the unit will be lower. With the assumption that the second hand price of these machines is between 10% and 20% of the new prices and that since half the throughput is needed, half the price is required, the price of the disc refiner is assumed to be €100,000.

8.1.4 Fiber-protein separation step (S01)

The step of separating fibre from liquid is called solid/liquid separation. There are several methods to separate liquid and solid which are listed in table 8-2.
The choice of equipment depends on the concentration of solids, the feed rate and the size of the solid particles. In the case of this process, the solid phase is fibre and uncut grass cells, the liquid phase contains protein, sugar, water and ashes. The fibre and grass cell concentration is 10.6% (appendix 5-2, table A5-9). Since we need clean and dry fibre for gasification to produce energy, the cleaning and the degree of dryness of the fibres are considered.

The average size of proteins is about 1.5-6 [13] nanometer, wheere the average size of plant cells is, according to an online encyclopaedia [14], about 100 micrometer. The size of the fibres can be a fraction of this size, but is assumed to be not smaller than 10 micrometers.
According to table 8-2, it is obvious that filtration equipment is more suitable for our separation.

Table 8-2: Different solid/liquid separation options [15]

Name technique	Principle	Particle size	Final Solid concentration
		[μm]	[%]
Thickeners and clarifiers	Sedimentation	60-500	<40
Filtration	Selected by size	lower than 60 up till 8000	0-90
Centrifuges	Selected by size	60-8000	0-90
Hydro cyclones	Centrifugal force	4-500	5-50
Pressing	Expression	-	>50
Solids drying	Evaporation	All sizes	>80

Table 8-3: The requirements

	Particle size [μm]	Ingoing solid concentration	Outgoing solid concentration	Feed rate [kg solid/s]	Energy cost [kW]	Equipment cost [€]
Requirements	> 10	10.6%	95%	0.35	< 100	~200,000

The particle size of fibre after disc refiner is at least larger than 10 μm. The fibre cakes will be burnt in the gasifier. The lower the water content, the better, so the outgoing water concentration should not be larger than 5w%.
Considering the total energy and equipment cost, the energy cost is set to be less than 100 KW (half of the disc refiner), and the equipment cost may be no more than €200,000.
For filtering, different methods exist, which are explained in appendixTiany1. There is also explained why for the rotary drum filter was chosen.

The solid components in the feed are fibre and grass cells; all other components are water and dissolved ash, protein and sugar. For the outgoing solid concentration the value is set at 5% water still present. This is water outside the cells. Inside the unbroken cells is also still water present. Since 85% of the cells are broken, and 8% of the content of the broken cells is fibre, 69% of the fibre and grass cell cake are grass cells. Inside of the grass cells 73% is water, so even if all free water can be removed, the cake contains at least 48% water from inside the cells. If the moisture content of the cake is 5% the total amount of water is 60% on mass basis.
Even the 48% is not acceptable for the gasifier. The solution for this is to dry the wet cakes with hot air. Since this unit is needed anyway, the water content after the rotary drum filter can be chosen. From literature [16] it is found that the moisture content is typically 30%, which means that in every 100 kg of cake, 30 kg of water is present.

Compared to the data from reference [16], the stream coming from the disc refiner is similar to the sugar cane mud. Thus, we set the characteristics of rotary drum filter same as those of sugar cane mud:

Table 8-4: Characteristics of the incoming stream and rotary drum [16]

Solid content		10.6%	By mass
Solid handling rate		0.03	kg dry matter / (s · m^2 filter surface)
Moisture content of cake		30%	kg water per 100 kg solids
air flow	through the filter surface	0.005	m^3 / (s · m^2)
	the vacuum pressure	0.3301	Bar below atmospheric
	the vacuum pressure	0.6699	Bar absolute
Submerged area		33%	Of the drum
Solid flow rate		0.35	kg / s

$1[kgforce/m^2] = 9.81e^{-5}[bar]$

$1[kN] = 101.97[kgforce]$

$33[kN/m^2] = 33*101.97 = 3365.01[kgforce/m^2] = 3365.01*9.81e^{-5} = 0.33[bar]$

Since the vacuum pump pressure is 33 [kN/m^2] below atmosphesric pressure,
which is equal to 0.33bar, and 1 [atmosphere] = 1.01[bar],
then, the vacuum pump pressure is :1.01-0.33=0.68[bar]

From the solid handling rate, the filtration surface area can be worked out. Set 33% of the surface area of drum is set to be submerged in the liquid phase. The solid in the stream going to the filter cake is about 0.35 kg/s.
So the surface area submerged in the liquid is about 0.35/0.03=11.8 m^2, the total surface area of the drum is 11.8/0.33=35.68 m^2. If the diameter is set at 2 meter, the face length of the drum is about 35.68/(2*Pi)=5.68 meter.

Table 8-5: Summary of the sizes of the rotary drum filter

Submerged area	11.8	m^2
Drum surface area	35.7	m^2
Diameter of drum	2	m
Drum face length	5.7	m

The composition of the Rotary Drum Filter System

The system includes a rotary drum with time periods devoted to filtration, washing and drying, string discharge system and cake conveyer.
The filter is made from cloth with holes in it of around 1-5 μm.
Four zones divide the drums inner space: cake formation zone, cake washing zone, dewatering zone and the cake discharge zone. The surface of the drum does rotating movement.

The slurry is saturated onto the drum when parts of drum submerge into it. Washing is needed to get off more protein, sugar and ashes from the fibre and grass cell cake. Most of water is drained out on the top of the drum after the washing step. The string discharge technique is introduced to collect the fibre cake which is transported by a conveyer belt.

Operation conditions:
The operating conditions influence the formation of a fully dischargeable cake. Thin cakes are desired, in order to get good cake washing, and drying, and a high capacity [17].

It can be assumed that the fibre cake is incompressible. The flow rate of solids is 0.35 kg/s, with the density of the filter cake of 500 kg/m^3 (appendix 5-2, table A5-5), the volume flow rate of the produced cakes is 0.35/500=$7 \cdot 10^{-4}$ m^3 per second. Assuming that the drum rotates at 0.25 rpm [18] and the diameter of drum is 2 meters, then the drum has a velocity of 0.05m/s.

$1[\text{rpm}]=\pi*\text{radius}[\text{m}]/60[\text{s}] = 3.14*2/2/60 = 0.05[\text{m/s}]$

$\text{surface linear speed} = 0.25*0.05[m/s] = 0.0125[m/s]$

In 4 minutes, the filtration area is: $0.0125[m/s]*240[s]*5.68[m] = 17.04[m^2]$.

the amount of solid produced in 4 minutes is: 240[s]*0.35[kg/s]=84[kg]

then, the volume of cake produced on the drum is: 84[kg]/500[kg/m^3]=0.168[m^3]

so, the thickness of cake formed on the drum in 4 minutes is: 0.168[m^3]/17.04[m^2]=0.0099[m]=10[mm]

The mass of the washing water needed is equal to 2 to 5 times the mass of the cake [19]. Since the difference in size is large (factor 10,000) and sugars and protein are water soluble, 2 times the mass will be enough to get 95% recovery of the protein, ashes and sugar.

Table 8-6: Summary of the designed rotating drum

Name	Amount	Unit
Duration	4	minutes
	240	s
Filtrate rate	0.03	kg solid/(s m^2)
	7.2	kg solid/m^2
Speed	0.25	rpm
	0.052	m/s
Diameter	2	m
Width	5.68	meter
Area (4 minutes)	71.4	m^2
Amount of cake (4 minutes)	514	kg solid
Density of cake	500	kg/m^3
Volume of cake	1.03	m^3
Thickness of cake	0.0144	m
Amount of washing water	381	kg/hr

One pump is needed to feed slurry into the drum container, one filtrate pump removes the discharged liquid and one vacuum pump (P06) to pull air out (appendix 5-8).

Cleaning operation cost and time cost depend on the complexity of equipment and the needed degree of cleanliness. In Zambia and China, this is not a problem since they have cheap labours to do cleaning. But in the Netherlands, this obviously increases the operation cost for this step. An alternative method is to use a cloth cleaning system. In Zambia labour will always be cheaper than a machine that only works a few times per day, and only 180 days a year.

According to reference [20], the cost for a rotary drum filter is estimated around €220,000.

8.1.5 Dryer (X06, T02)

Rotary drum filter/dryer combination
The rotary drum itself gives fibre cakes with 30% moisture content, and all grass cells still have their 73% of water inside the cells. Thus, as is said above, the total amount of water in the fibres is 60% on mass basis. In order to get fibres that can be burned in the gasifier, the total water content is preferably 5% and at most 30% on mass basis.

For the design of the rotary drum filter only the submerged area is taken into account. This is 33% of the total area. On the real drum, 33% of the area will indeed be submerged and another 33% will be used for the washing and drying to 30% free water content (60% total water). This means that there is about 20% of the area of the rotary drum left before the cakes are scraped off. This area can be used to dry the cakes with the help of steam. The total area of the drum is 35.7 m^2, so the heat transfer area for the drying part is 7.1 m^2. According to [21] the estimated evaporation capacity is 0.01 kg water / ($s \cdot m^2$). This gives an evaporation rate of 0.071 kg per second. The total water flow in the cake is 0.28 kg per second, so this area is not enough to get below 30% (the total water amount is still around 60%). So another solution is needed, which is drying with hot air, as described below.

Air-drying
The humidity in Zambia is on average 55% [refJefhum1]. According to table 16.1 in [refJehum2] the moisture content of wood at 55% humidity is around 9% and that of wool around 13% (both percentages on mass basis). Since the dried fibres will have a composition somewhat similar to that of wood, the estimated moisture content of the cake is 10% on mass basis when it is contacted with the outside air in Zambia.

Another solution is needed and according to literature [22] fibre cakes for gasification are dried with hot air. Since the fibre and grass cell cake leaves the rotary drum filter by means of a conveyer belt, this conveyer belt is used to transport the cake trough a hot air oven (also called a conveyer dryer or a continuous circulating band dryer).

The inlet flow of the belt dryer is the cake from the disc refiner. The flow rate of this stream is 0.46 kg/s. The total water content is 60%, which needs to be reduced to 5% of the total stream. This means that 0.27 kg of water needs to be evaporated per second. A typical evaporation capacity for a dryer is 20 kg water / ($h \cdot m^3$) [23]. This results in a volume of 48 m^3 for the dryer.

The width of the rotary drum is 5.7 meters. This is too wide for a conveyer dryer (the weight of the top is too much to handle for a steel bar without support), so the conveyor belt will be 3 meters wide. The height of the unit is around 1 meter, so the dryer will be 16 meters long. The maximum height of the cake can be 10 cm [24], so the speed of the belt must be 0.19 m/s.

The amount of energy input is equal to 3 times the amount of energy needed for the evaporation of the water [24]. It is needed to evaporate 0.27 kg water per second. In the design, the latent heat of evaporation was taken at 2.3 kJ/kg, instead of $2.3 \cdot 10^3$ kJ/kg. This results in an energy input of 1.85 kW, instead of 1800 kW.

The cost for this drier is based on three belts of 1 meter width and will be €127,000 in total [25].

After the fiber cakes are dried, they will be stored in a storage tank (T02). The mean amount of storage will be 436 ton per year (this is the amount needed for half a year in which there is no production of fiber cakes). With a density of 500 kg per cubic meter, the volume needed is 218

m^3. Because people still must be able to walk in this storage facility and just in case some extra volume is needed, this volume is multiplied by 2. Assuming a two meters high bunker, the ground area will be around 15 m by 15 m.

The costs for this storage facility will be € 75,100 [2].

8.2 Protein production

After the proteins are separated from the fibres and grass cells together with the sugars and ashes, this stream still contains a lot of water. To reduce the storage facilities and to make it easier to feed the pigs, this large amount of water must be reduced. To accomplish this, an evaporator and a Rotary drum filter are considered, as discussed below.

8.2.1 Evaporator system (E01)

Evaporation is normally used to produce a concentrated liquid through removal of the solvent. In this process, evaporators are used to concentrate the protein/sugar solution, which finally becomes protein cake. Considering minimization of heat consumption and costs for the system, a multi-effect evaporator is more preferable in the case of huge amounts of solvent in the solution that need to be evaporated, in combination with high steam costs. In this process, a lot of water needs to be removed from the solution, but the condensing steam can relatively cheaply be obtained from gasification. Thus, a small heat exchange area is the decisive economic criterion rather than steam costs.

In multi-effect evaporators [26], the steam to cause evaporation is fed at a high enough pressure and temperature to the coils of the first effect there, an amount of water is evaporated from the solution equivalent in latent heat to the quantity of steam condensing. This evaporated water serves as condensing steam to cause evaporation in the second effect, and so on. In order to be a driving force for heat transfer in the desired direction across the evaporator coils, each successive effect must operate at a lower pressure than the one before.

Starting with design of a 4-effect evaporator system, it is afterwards compared with other possibilities, i.e. 3, 2, 1-effect system. It is found out that one evaporator is the best option from economic and techniqual view, see appendix 5-4. In table 8-7, data for the best option of a single-effect evaporator are listed.

Table 8-7: Summary of evaporator with 1 stage

Single stage	Value	Unit
Pressure	1	Bar
Heat transfer coefficient	3000	$w/m^2/k$
Heat transfer area	35.17	m^2
Condensing steam needed	2.34	Kg/s
Steam generated (recycled)	2.05	Kg/s
Additional condensing steam needed	0.29	Kg/s

In general, evaporators fall into the following basic types [27]: Direct-heated, Long-tube, Natural-circulation, Forced-circulation, Agitated thin-film, and Short-tube.

The selection of the most suitable evaporator type for a particular application depends on the following factors required throughput, viscosity, nature of the required product (solid, slurry, or concentrated), heat sensitivity of the product, foaming, fouling, and other feed conditions. The most important factors are the viscosity and the conditions of the feed stream.

During evaporation the viscosity changes from low to medium. Because the sugar solubility will change by heating and because less water is available (most water evaporates), the viscosity will rise. An apparatus should be chosen that could handle different kinds of viscosity.

Proteins are very heat sensitive. The heat needed for evaporating the water can also precipitate the proteins. For selecting an evaporator, it should be suitable for heat sensitive materials. Assuming precipitated proteins behave almost the same as foaming, an evaporator who can handle foaming is needed.

Taking these three things into account, table 8-8 from reference [27] leaving two options; Forced circulation and Single pass wiped film. Because industrial knowledge about Forced Circulation is much better in comparison to Single pass wiped film, the first one is chosen. There are two types of forced-circulation evaporators: Submerged tube and boiling tube, and the first one is currently widely used in the industry [28], and is chosen for this process.

Table 8-8: Types of evaporation with the conditions of the flow needed.

	Feed conditions							Suitable for
Evaporator type	Viscosity, mN s/m^2			Foaming	Scaling or fouling	crystal productd	solids in suspension	heat-sensitive materials
	high>1000	Medium <1000 max	low <100					
Recurculating								
Calandria (short vertical tube)		←	—	—	—	—	→	NO
Forced circulation		←	—	—	—	→		YES
Falling film			←→					NO
Natural circulation			←	→				NO
Single pass								
Wiped film	←	—	—	—	—	—	→	YES
Tubular (long tu								
Fallin gfilm			←	→				YES
Rising film			←	→				YES

The costs for an evaporator are € 21,000 [29]. Although this was the cost in 1998, same number is used for now.

8.2.2 Remaining water removal (X05)

Althrough the sugar/protein stream already losses a lot of water during evaporation, there is still too much water in the protein cakes. To reduce the amount of water at first a rotary drum filter was seen as the best option. After designing (see appendix 5-5) it was determined that the costs were very high and the protein particles were very small.

Another solution is needed. A better option is to dry the protein-sugar solution further with hot air. Because this principle is already used for fibre cake drying and because it is simple, this was found to be the best solution.

The inlet flow of the belt dryer is the flow from the evaporator. The flow rate of this stream is 0.25 kg/s. The total water content is 30%, which needs to be reduced to 10% of the total stream.

This means that 0.08 kg of water needs to be evaporated per second. A typical evaporation capacity for a dryer is 20 kg water / (h · m^3) [23]. This results in a volume of 14.4 m^3 for the dryer.

The conveyor belt will is assumed to be 1 meter wide. The height of the unit is around 1 meter, so the dryer will be over 14 meters long. The maximum height of the cake can be assumed to be 1 cm, so the speed of the belt must be 0.05 m/s (0.228 kg cake per second, with the density of the cakes being 500 kg/m^3).

The required energy input is assumed to be equal to 2 times the amount of energy needed for the evaporation of the water [24]. 0.08 kg water per second needs to be evaporated. Since the evaporation energy for water is $2.3*10^3$ kJ/kg the energy input is 410 kW.

The cost for this drier is €27,000 [25].

8.2.3 Protein cake storage (T05)

After the protein cakes are dried, they will be stored in a storage tank (T05). The total amount of protein cakes produced is 2,300 ton per year. The maximum capacity of the storage facility should be half of the total amount protein cakes produced. This is based on the fact that in half a year time, protein cakes for a whole year are produced. With a density of 500 kg per cubic meter, the volume needed is 1,200 m^3. Because people still must be able to walk in this storage facility, and in case some extra volume is needed, this volume is multiplied with 2. Assume a two meters high bunker, the ground area will be around 50 m by 50 m.

The costs for this storage facility will be € 226,800 [2].

8.3 Gasification

The fibers from the fiber-protein separation step will be converted into electricity, which is used to run the whole process. In this paragraph, a design for the gasifier is given.

8.3.1 General introduction of gasification

A gasifier is a system, which converts biomass or other carbon sources into combustible gas ('producer gas') using thermal processes such as pyrolysis. Biomass is combusted imperfectly by way of controlling the flow of air or steam into the gasifier to convert the solid energy carrier into a gaseous one, generating a combustible gas, which consists mainly of H_2, CO, CH_4, and C_nH_m. CO_2 is also formed, and in case air is used N_2 is also present.

The conversion of the producer gas into electricity generation is commonly achieved in one of the following 3 ways:
Producer gas is used to fire boiler to produce steam, which then drives a steam turbine to generate electricity.
The producer gas is cleaned and drives a gas turbine to generate electricity
The producer gas is cleaned and drives a gas engine to generate electricity
Above pathways correspond to large-scale, medium-scale and small-scale electricity generation, respectively.

For this small-scale process, the team decided to use the technology of biomass gasification for electricity generation using gas engines, because of the small system capacity with reasonable efficiency, low investment costs, good reliability and simple operation. Maintenance and operation costs are low [30]. A simplified scheme of gasification and electricity production is shown in figure 8-1.

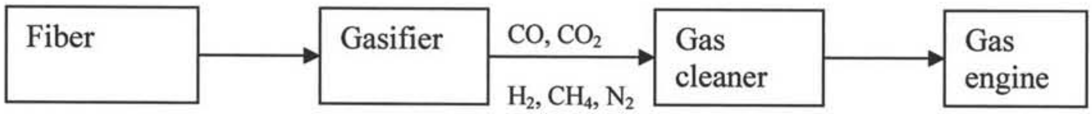

Figure 8-1: Electricity generation systems equipped with a gas engine

The gas temperature in the outlet of the gasifier is often in the range of 350°C ~ 650 °C, or even as high as 1000 °C, depending on the type of gasifier. The gas contains impurities such as dust and uncracked tar. In order to meet the demand of reliable gas engine operation over a long period of time, it is necessary to cool the gas at temperatures below 40 °C, and to reduce the content of dust and tar to below 50 mg/Nm^3.

After cleaning, the gas is fed into the gas engine to generate electricity. In the gas engine, the gas is mixed with air, and combusted. The engine then drives the generator to generate electricity.

Through above procedure, any carbon containing waste can be converted into electrical energy, turning waste into (valuable) resources [1]. Emissions are low compared to other processes, as long as proper requirements on heavy-metal content etc. are made. Electric efficiency lies around 20%, yielding a thermal heat availability of 4x the electric power availability.

Process utilisation
Based on literature, l kg/h biomass can produce approximately 1 kW of electricity through gasification [30,31]. In the small-scale process, the energy requirement of the non-gasifier section of the process will be approximately 400 kW. This power is not required continuously, but concentrated in the daylight hours. During process downtime, there still is an electricity demand, assumed not exceed 60 kW (total energy consumption on farm and any community nearby). This calls for great flexibility in power generation. The gasifier will consume 330 kg/h of biomass continuously, filling gas storage at night, and emptying it by day.

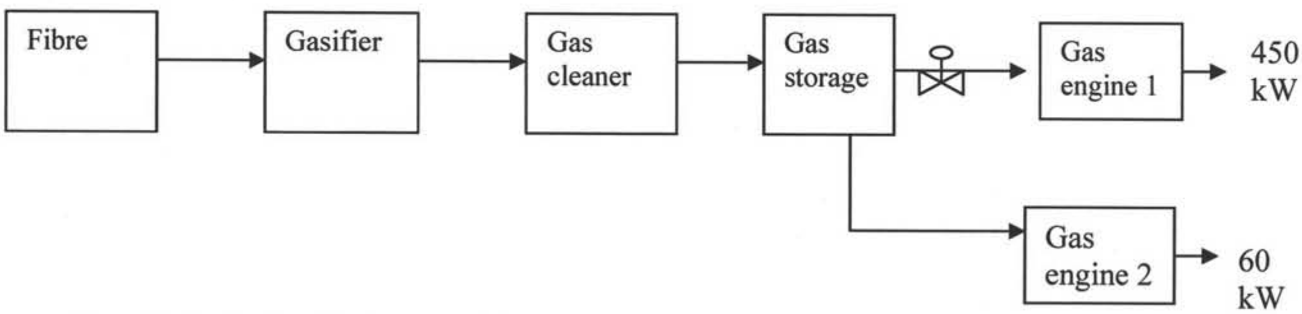

Figure 8-2: Small-scale gasification process design

In gasification, organic compounds are thermally pyrolyzed and cracked. Although gasifiers can be started up quickly, it is preferable to keep the gasifier running continuously to circumvent losses in the cooling and reheating of the reactor. The continuously formed producer gas is stored during the downtime of the process (at night). This stored gas is later used to produce process electricity on demand in gas engines.

Gas engines are available in different sizes and types. Internal combustion (IC) engines and diesel engines are often used (both on producer gas and on fuel/gas mixtures), but Stirling engines are also considered. Many alternative modes of electricity production are available, and even hybrid engines (Stirling + IC) should be considered; thorough analysis of these options is recommended.

In this design, only limited focus is brought upon the actual type of engines used. Instead, average specifications of gas engines used in biomass gasification are applied. Currently, 200kW converted diesel engines are quite popular, while larger engines are available. The problem with the diesel engines is that they still require 20-30%w of their fuel to be diesel. Even at this relatively small scale, this would require around 1-1.5kton diesel per annum. Since the final objective is to produce good fuel, and total ethanol production is estimated at 400ton/farm, this is not a good option. Instead a dedicated gas engine will be chosen, despite it's extra cost.

To maintain good efficiencies, a separate smaller engine is used to generate power needed on the farm during downtime of the process. Depending on the actual combined power use of the plant and the farm, the two engines might or might not be required to run simultaneously [32,33,34].

8.3.2 Gasifier (R01, X07)

Gasification on large scale is popularly done in fluidized bed reactors. Downdraft gasification on the other hand, produces a low particulate and low tar gas, at the cost of lower production rate, and is therefore more suited for power generation in small-scale applications.

An elevator (X07) transports the fiber cakes into the gasifier. The fiber cakes are fed to the gasifier at the top. The gasifier will be around 3 meters high, requiring a 3-metr elevator. At an angle of 30^0, the length of the elevator belt is 6 meters long.

The cost for this elevator is € 31,300 [7].

Calculations on the gasifier were done using a gasifier-model created at the DTU in Denmark [12]. Variables used were: stream preheating temperatures, gasifier temperature, CH_4 content in producer gas, fuel composition and steam flow rate. Ranges over which they were varied are shown in Table 8-9.

Table 8-9: gasification variables

Variable	Min. value	max. value
Air preheat T [°C]	400	600
Steam preheat T [°C]	400	600
Gasifier T [°C]	600	1000
CH_4 content [%]	1	3
Steam rate [kg/h]	0	50
Moisture content [% on dm]	5	15
Biomass composition	$CH_{1.5}O_{0.7}$	$CH_{1.7}O_{0.8}$

Furthermore, heat loss of 3% and an unconverted charcoal production of 1% were assumed. An evaluation of the effects of these variables on thermal efficiencies and the lower heating value (LHV) of the producer gas was made.

From these explorations, it was clear that the main factors influencing efficiency and LHV of the gas were water content, gasifier temperature and steam content. The effects of preheat temperatures are significantly smaller, and only theoretical (in practice, we do need energy for preheating). Best efficiencies and heating values are found at low reactor temperature, low water content, and low steam content. However, at these conditions, reaction rate and conversion are rather low.

Biological feedstock can vary greatly even over the course of a season, setting the demand of a flexible gasifier. If at any time higher cracking activity is needed, fibre drying will be decreased, followed by gradual increase in temperature and steam feed. Another important reason for wanting a flexible, stable gasifier, is future development of the project: if fibre is to be converted to ethanol, another biomass source (likely with dramatically different properties; e.g. domestic waste) needs to be used.

The reactor has to be able to operate in the range of 600-1000K, and needs a flexible intake capability for steam and air. Reactor specifics are given in appendix 5-6. Exhaust gases are used to preheat incoming air, cooling them down to 40°C. Gasifier cost is based on [35]. Scaled down to 330kW, and compensating for economy of scale, the gasifier is expected to cost 400k€.

8.3.3 Cleaner (S02, S03, T03)

The producer gas can contain amongst others corrosive compounds, NO_x, tars and chars, which can be harmful to the engine. The flow rate of gas into the storage tank is quite small (~ 650 Nm^3/h). The gas itself needs to be cleaned to a particulate level below 50 mg/m^3, and any tars should be removed.

For the fines separation, a baghouse is chosen, with a surface area of 8.9 m^2. This baghouse filter does not reduce the estimated fine particle content (10 g/Nm^3 [36]) below it's legal boundary of 0.02 g/Nm^3. Final purity is obtained by running the filtered gas through a higher efficiency (99%), but low capacity, cartridge filter. The cartridge filter also acts as a policing filter. When catalytic tar conversion is better developed, a converter will be placed before the baghouse.

The exhaust of the engine needs to be cleaned as well, to remove NO_x in compliance with emissions regulations. For this a standard three-way catalyst, integrated in the engine, is used.

The gas from the gasifier needs to be stored before it goes to the engine. For this storage a spherical tank (T03) is used with a radius of 4.1 meter, which gives a volume of 293 m^3. The pressure in this storage facility will be 25 bar. The density of the gas will be (in ideal conditions) 21.2 kg/m^3. The costs for T03 will be € 89,000 [37].

8.3.4 Gas Engine (R02)

In general, diesel and gasoline engines can be converted to operate on gaseous fuels However, gas-fuelled diesels still require around 20w% diesel to operate, while gasoline engines require high quality gas. The diesel engine is more attractive for the combustion of producer gas as the reduction in power and efficiency, due to the higher compression ration and excess air, is less compared to an Otto engine [38]. The amount of diesel required is more than the maximum theoretical ethanol production (see chapter 2.4) per farm, leaving the choice for an engine running only on gas. A small 60kW diesel engine will be used in dual-fuel mode, to supply energy during times of low demand.

The costs for the 450kW_e gas engine is estimated based on the cost of a Jenbacher 300-series cogen-set of 1,250€/kW_e [39], resulting in a total engine cost of 562.5k€.

Storage tank for ashes (T04)
Ashes from the gasifier (43.7 ton per year) and the filter section (28.1 ton per year) are stored before they are returned to the soil. With a density assumed at 1000 kg/m^3 the volume of the tank

is around 72 m^3. Because it is not really necessary for people to walk in the storage tank, a total volume of 100 m^3 will be enough. With a height of the tank of 2 meters, the ground area is 50 m^2. The cost for the ash storage facility will be € 26,500 [2].

Water recycle buffer tank (V03)
Although all water is either reused immediately or disposed, a water buffer tank will be installed. This is done in case something goes wrong in the process. The volume of this tank is assumed to be 25 m^3. With a diameter of 2 meters, the length of the tank is 8 meters.
The costs for the water storage vessel are € 15,500 [2].

8.4 Heat Exchangers

Two heat exchangers are used in the process; E02 is used to preheat air before it enters the gasifier, and E03 is used to cool process water down to 30°C. Specifics are given in table 8-10.

Table 8-10: Specification of the heat exchangers

EQUIPMENT NR.: **NAME :**	**E03** **Gasifier air preheat**	**E02** **Water cooling**
	Floating head heat exchanger	Floating head heat exchanger
Substance **Tubes :** **Shell :**	air producer gas	water CW
Duty [kW] :	91.85	124.49
Heat Exchange area [m^2] :	32.7	10.10
Pressure [bara] **Tubes :** **Shell :**	atm atm.	atm atm
Temperature **In / Out [°C]** **Tubes :** **Shell :**	25.0 / 656.0 661.0 / 554.2	50.0 / 35.0 25.0 / 35.0
Special Materials of Construction :	Tubes : SS Shell : SS	Tubes : CS Shell : CS

The calculations can be found in appendix 5-4.

8.5 Pumps

Pumps are employed for the transport of liquids or gases from one vessel to another or through long pipes.

Criteria for pump selection
Pump selection is based on the flow rate, head required, the concentration of solids in the fluid, and the viscosity of fluid. Normally two types of pumps are used: Dynamic pumps (such as centrifugal pumps) and Positive displacement pumps.

Pump choice factors:
- The quantity of liquid to be handled – affects the size of pump.
- The head against which the liquid is to be pumped – affects the suitability of a centrifugal pump and the number of stages required.
- The nature of the liquid to be pumped – affects the power required and the material of construction.
- The nature of the power supply. (A centrifugal and rotary pump are driven by electric motor, reciprocating pumps use internal combustion engines).
- Used continuously or intermittently.

Cost and efficiency.
Considering the above factors the centrifugal pump has the advantages of pumping liquids with very wide-ranging properties and suspensions with a high solids content they can be coupled to an electric motor and give a comparatively high flow rate for their size. It is a promotive choice in our process design.
Determination of size and power requirements

1. Position of pumps in relation to the flowing sheet

Table 8-11: Summary of pumps and blowers

No.	Description
P01	sieved liquid
P02	washing water
P03	washing water to the refiner
P04	washing water to the sieve
P05	waste water
P06	mixture without fiber
P07	water out of evaporator
P08	concentrated sugar liquid
P09	water to furnace
K01	air supply
K02	gas from gasifier
K03	gas after filter
K04	steam to furnace

2. According to the characteristic curves for centrifugal pumps and the different flow rates in different position of process [40], the detailed calculations are given in appendix 5-8. The result of pump selection is listed in the Table 8-12.

B Blower and Fans

Blower K01 is used to supply draft air to the gasifier. Fan K02 and K03 are used to move large volumes of gas with high flow but low-pressure conditions. Axial-flow fans are selected to handle very high flow rates and low pressure. Since the gasifier produces some ash and tar, and the gas has a high temperature should also be considered as important factors for the fan type selection. The rotors (2-stage propeller type) have 4 to 12 blades and usually operated at low speeds. These fans are used especially for gases at high temperature and with suspensions in the flow stream. Select forward-Curved blade blower to supply gas for the gasifier with high speed: 3600-1800 rpm in 60-cycle countries or 3000-1500 rpm in 50-cycle countries.

The power needed to drive the fan is calculated by the formula:

$\text{Power(kw)}=2.72*10^{-5}*Q*P$, where Q is the fan volume (m^3 / hour)

and P is the total discharge pressure in cm of water column.

Assumed that 80% pressure of highest efficiency can be achieved. According to the characteristic curves of fans [41]

To calculate the power, the total discharge pressure needs to be known. The increased pressure drives the gas against the frictional force it experiences while flowing through the pipes. [42].

Assumptions: Assume the pipeline is 10 meters for air input, 4 meters for gas transport from the gasifier to the bag house (1033K), 4 meters transport from the last filter to the diesel engines (313K), and 8 meters transport from the evaporator to the furnace (323K) The diameter of pipelines is about 0.3 meters. The density of air is 1.29 kg/m3, gas is 1kg/m3 at around 1033K, 1.1 kg/m3 at 313K, and steam is 0.0936 kg/m3 at 323K [43].

The calculation result is listed in Table Pump 8-12.

Table 8-12 Pump and Blower Design Result

No.	Type	Density [kg/m3]	Flow rate [m3/hour]	Head [m]	Power [kW]	Annum power [kWh/a]
P01	Centrifugal single stage	800	1.44E+01	40	1.48E-03	4.2624
P02	Centrifugal single stage	1000	4.34E+00	32	3.26E-04	0.93888
P03	Centrifugal single stage	1000	5.63E+00	32	4.23E-04	1.21824
P04	Centrifugal single stage	1000	2.45E+00	32	1.84E-04	0.52992
P05	Centrifugal single stage	1000	4.06E+00	32	3.05E-04	0.8784
P06	Centrifugal single stage	970	1.26E+01	32	9.54E-04	2.74752
P07	Centrifugal single stage	1000	1.25E+01	32	9.39E-04	2.70432
P08	Centrifugal single stage	1100	1.24E+00	32	9.31E-05	0.2681
P09	Centrifugal single stage	1000	1.55E+00	32	1.16E-04	3.34E-1
K01	Blower	1.29	2.72E+02	5.58E-05[bar]	4.21E-04	1.21
K02	Blower	1	1.34E+03	2.4E-04[bar]	8.92E-03	2.57E+01
K03	Blower	0.91	1.45E+03	2.64E-04[bar]	1.06E-02	3.06E+01
K04	Blower	0.0936	6.05E+03	2.66E-03[bar]	4.46E-01	1.28E+03

8.6 Ethanol production on small scale

This chapter is not designed in the way the rest of the process is designed. In an early stage it was determined that ethanol production gave too high an initial investment, so it was decided not to design this part. But during the design of the small-scale plant it came apparent that the costs of that plant were higher than we had expected. Together with the fact that our coach and the principals wanted to see this part it was decided that there were calculations needed for this process part. Below is the design of the most important units (cost factors). In appendix 6 a raw flow scheme is drawn of this process with also only the mayor equipment in it.

8.6.1 New sugar protein separation

In the small-scale process the sugar and protein are used together in the protein cakes. In order to produce ethanol the sugar must be separated from the protein. An ultra filtration membrane unit will be used for this separation [44]. Since the proteins are bigger than the holes in the membrane, 99% of the protein will be hold by the membrane. Furthermore it is assumed that about 3 % of the ash and sugar will be left in the protein cake.

In order to change as little as possible to the original process, the same evaporator will be used. This means that the stream towards the ultra filtration unit is the same as the one leaving the evaporator. With the assumptions of the filtration efficiency above, this gives a sugar stream of 11.6 kton per year, with a sugar concentration of 41.1% on mass basis.
The protein will be washed from the ultra filtration unit and treated the same way as in the small scale. But there is much less sugar, which gives protein cakes with a purity of 80%.

This highly concentrated sugar stream is stored when it is produced at the farm and transported (see chapter 12) to a central location, where the sugar water is collected from (for the first pilot plant) 3 farms. At this central plant the ethanol is fermented to ethanol and this ethanol purified. The storage facility must be big enough to store the sugar water for half a year since sugar production is half a year, but ethanol production will be run year round. This means that at the end of the half year production, half of the total produced sugar water must be stored, which is 5.8 kton. Since this consists mostly of water, the density is 1000 kg per m^3 requires a 5800 m^3 storage vessel. On the site of matche [45] it was found that this is too big for one storage tank, so 3 smaller ones of 2000 m^3 (6 meter high, 21 meter in diameter) each will be bought. The price for one of these vessels is 122 thousand euros so the total cost of the vessels will be € 366,000.

8.6.2 Ethanol production

Yeast is used to convert the sugar into ethanol. The sugar is converted without oxygen (anaerobic). However, under anaerobic conditions the yeast only grows very slow, requiring to be grown the yeast aerobically before it is placed in the fermentor. After the fermentation the yeast can be used again, but since a part of the yeast dies and other parts mutate to be less effective every batch a percentage of new yeast is needed. It is assumed that 3% of the input sugar is needed to grow new yeasts.

About 75% of the total sugar amount is assumed to be convertible to ethanol. The rest is assumed to be non fermentable by the yeast. From [46] it is known that 55% of the converted sugar mass will become CO_2, 40% ethanol and 5% others. Here it is assumed that 3% will become biomass, 1% acetic acid, and 1% furfural.

Table 8-13: Percentage of converted sugar to other components

Component	Conversion [%]
Ethanol	40
CO_2	55
Yeast	3
Acetic acid	1
Furfural	1

Since the new biomass requires nitrogen all proteins are used as nitrogen source and will be converted to biomass. The newly formed biomass also needs ashes (minerals), so 10% of the mass of the new biomass comes from ashes.
Yeast functions the best at temperatures around 35 °C. The conversion of sugar to ethanol is an exothermic process, so cooling is needed. Since the location of the ethanol plant is chosen near a water supply (see chapter 3.2.2), enough cooling water will be available to keep the temperature in the reactor stable.
Biomass cannot grow at too high concentrations of sugars, so 1.4 ton per hour of water will be added to get a 20% sugar solution. A normal fermentation of glucose takes 24 hours [47]. Since not all components in the plant sugars are as easily fermented as glucose, it is assumed that the residence time will be doubled for the above stated 75% conversion, which gives a residence time of 48 hours.

During fermentation CO_2 will be produced. This gas contains trace amounts of volatile organics and water. To ensure no environmental legislation will be violated, a small cooler is placed in line of the exhaust to condense the volatiles. After the cooler, the gas is bubbled through a water reservoir, which acts as a trap for non-condensed chemicals, and seals the fermentor from air.

Fermentation will take place year round. This results in a (fictive, because the fermentation happens batch wise) stream of 2.63 ton per hour. With the residence time this gives a total reactor fermentor of 126 m3. Since there will be idle time, the total volume is taken as 150 m3. On the website of an enzyme producing company [48] the price of a 150 m3 fermentor was € 4 million, but this is the total cost. Since there are in their case oxygen pumps and sophisticated other systems on it, the assumed price for the fermentor and all additional equipment for the process is € 2 million.
Since fermentation is batch wise, and the ethanol purification will be done continuously storage is needed in between. To be sure everything operating well, it is assumed that the total volume of the fermentors must be stored. This gives a volume of the storage vessel of 150 m^3 (6 meter high and 5.6 meter wide) and with [45] this resulted in a price of € 38,000.

8.6.3 Ethanol purification

The first step in ethanol purification is to get the solids (biomass) out of the stream, which is done by a rotary drum filter. It is assumed that all biomass can be filtered out and that the loss in all other components is 5%. This results in a stream with 6.0% ethanol on mass basis [appJeEth1]. On the small scale the costs of the rotary drums were high (in the order of 500 thousand euros) so here the price for the rotary drum is assumed to be 3 times that amount (stream is the combined stream from 3 farms), which gives 1.5 million euros.

The distillation of ethanol is modelled in Aspen®. Too many components slow down the simulation, so a choice of the components had to be made.
Ethanol is the product, so this one is needed.
Water is most plentiful, so it is taken into account.
Furfural and acetic acid are 2 common by products of ethanol production and distillation. So they are also taken into account.
CO_2 is plentiful produced in the reactor, but since it is not wanted to have a pressure increase in the reactor, this CO_2 is taken out of the reactor. By cooling the stream, the ethanol and water in the stream are condensed at returned in the fermentor. It is assumed to have no losses in water and ethanol. A small amount of CO_2 will still be dissolved in water, but this is not taken into account for the Aspen® simulation.

Ashes are left out the simulation, because they are not volatile. It is assumed that all ashes just flow with the water streams. Sugar is also not volatile, but on heating C5 sugars can form furfural. In order to model this effect, but not make the simulation too complicated, it is assumed that 5% of the incoming sugar is furfural, and the rest of the sugar is left out the simulation.
The modelled incoming stream in the simulation is given in Table 8-14 below:

Table 8-14: Composition of the incoming stream in the Aspen® simulation

Component	Flow rate [tonne/year]
Water	16587.00
Ethanol	1315.00
Furfural	87.67
Acetic acid	32.87

The specified temperature was 35 °C, which is the temperature of the fermentor. The pressure as 1 bar.

All components were present in the database, so these were chosen. The used model for the simulation was Wilson, as described in chapter 4. Also the Henry coefficients for all components were also added to the Henry list and the coefficients specified in Aspen® were used.

Two units were used to design the azeotropic distillation of water and ethanol. The first unit is a heat exchanger to bring the incoming mixture to its boiling point. This heat exchanger is modelled by a so-called heater block. The input of the block was a pressure of 1 bar and a vapour fraction of 0. The result was a stream of the same composition as above, but at a temperature of 92.6 °C.
By doing this, the liquid is at its boiling point, which is common practise in the use of distillation columns [49].

For normal separations (non-azeotropic) short cut calculations are normally made first , to find the number of trays and reflux ratio of a column. But for this highly non-ideal separation, the short cuts methods do not work. The reason for this is that in the shortcut calculations a constant selectivity factor α is assumed, or the average α for the top and bottom is used. But since this α is not constant in the case of a water/ethanol mixture, this procedure was useless.

For the simulation a RadFrac column block was used immediately. Some specifications were known beforehand, so they were chosen as input for the setup options. A total condenser was used, as a reboiler a Kettle, the valid phases were vapour-liquid and the convergence as azeotropic.
For the operation specifications the reflux ratio and the distillate to feed ratio were chosen. The first one was, together with the number of stages and the feed stage chosen as variable. The distillate to feed ratio is the ratio of the distillate flow over the feed flow. This value is known by setting the recovery of ethanol at 99.5% and the purity of the ethanol at 94.5%. The recovery is a standard value, and the purity was chosen to be a bit below the azeotrope. This resulted in a distillate to feed ratio feed of 0.077.

By trial and error it was found that a column with 27 stages, a reflux ratio of 9.1 and a feed stage at the 22nd from above resulted in the required purity and recovery. But this was only 1 solution, and not necessarily the best one. A normal rule for a distillation column is that the reflux ratio is 1.2 times the minimal reflux ratio, which often results in an amount of stages of 2 times the minimal number of stages [49] and [50]. The minimal number of stages occurs when there is total reflux.
In order to simulate total reflux the reflux ratio was set at 100,000. To get the required purity and recovery 19 stages were to few (99.48% recovery), while the requirements were met with 20 stages (99.54% recovery). The minimal number of stages is 20, so the real amount of stages would be in the order of magnitude of 40 stages.

To get the minimal reflux ratio, the amount of stages must be infinite. The reflux ratio was chosen to be 9.1, the same number that was found earlier to work with on 27 stages. Since an infinite number of stages cannot be modelled, the number of stages was chosen to be 200. Unfortunately, the program could not find a solution with this amount of stages, so the number was lowered to 150, to 100 and to 75, but still no solution could be found. When 60 stages were used, a solution was possible: 60 stages, feed stage 49 and reflux ratio of 9.1. To check if this solution was indeed in the range of almost constant reflux ratio, the same values were used but then at 61 stages. The value of the amount of ethanol in water (the loss of ethanol) was in both cases 0.283 kg per hour, so it was judged that constant reflux was indeed achieved.
By using 60 stages, stage 49 as feed and changing the reflux ratio is was found that the reflux ratio needed for 99.5% recovery was 3.56. This value was used as the minimal reflux ratio. According to the rule of thumb of actual reflux ratio is 1.2 times the minimal reflux ratio, thus the actual reflux ratio was 4.27.

By using a reflux ratio of 4.27 and changing the total number of stages and the feed stage, it was found that a column with 44 stages and adding the feed on-stage on stage 35 gave the required recovery of 99.5% and a purity of 94.28%. That the purity is a little below the required purity of 94.5% is due to rounding errors in the distillate to feed ratio. With the assumption that a stage is about half a meter high, and some additional meters are needed for construction, the height of the column will be 25 meters.

This column was judged to be the one that will be used for the azeotropic distillation. The results of the simulation are shown below in table 8-15 and table 8-16.

Table 8-15: Stream results from the Aspen® simulation:

Stream	Temperature [°C]	Pressure [bar]	Mass Flow [kg/hr]	Water Flow [kg/hr]	Ethanol Flow [kg/hr]	Furfural Flow [kg/hr]	Acetic Acid Flow [kg/hr]
Bio-out	35.0	1.0	2057	1893	150.1	10.0	3.75
Dest-in	92.6	1.0	2057	1893	150.1	10.0	3.75
Ethanol	77.7	1.0	158	9	149.4	TRACE	TRACE
Water	99.4	1.0	1899	1884	0.8	10.0	3.75

As can been seen, there is almost no (less then $1 \cdot 10^{-16}$ kg per hour) furfural and acetic acid present in the ethanol stream, so no extra measures are needed to remove those.

Table 8-16: Condenser and reboiler results from the Aspen® simulation:

	Temperature [°C]	Heat Duty [kW]	Reflux Rate [kg/h]	Reflux Ratio [-]
Condenser	77.7	-216	677	4.27
Reboiler	99.4	231	382	0.20

With correlations in [49], the gas velocity could be calculated. The maximum gas velocity was 28 m/s and it is normal to take 80% of this value to prevent flooding, which results in a velocity of 22 meter per second. Together with the reflux ratio the amount of gas in top of the column could be calculated, and together with the velocity of the gas, the diameter of the column is 5.3 meters.

With cost estimations in [51] the costs for the column will be 1.61 million euros if stainless steel clad carbon steel is used. Stainless steel is needed on the inside of the column, since hot water is corrosive. To make the column less expensive, carbon steel is used as support, instead of a total stainless steel column.

The internal of the column will be filled with random packing. Columns with real plates require higher maintenance than packed columns. Random packing will be used because it is cheaper than structured packing, since the investment costs should be as low as possible. The price of stoneware saddles of 25 mm is 1400 euro per m^3 [52]. The total volume of the column is 550 m^3, so the costs will be 770 thousand euros.

Table 8-17: Summary of the ethanol distillation column.

Number of stages	44
Reflux ratio	4.27
Height	25 m
Diameter	5.3 m
Volume	550 m^3
Cost of column	1.61 million
Cost of packing	0.77 million

8.6.4 Ethanol dehydration

To be able to sell ethanol as a fuel, the water content must be lower than 1%. In order to reach this value across the azeotrope, several options are possible: a column with a higher pressure, adding a third component or using a molecular sieve. The disadvantages of a higher pressure are the high costs and higher risks. The disadvantage of adding a third component is that it makes the separation more complicated (in case of adding benzene, 3 columns and a decanter are needed [53]). A molecular sieve can operate at ambient pressure, requires only a few, but identical, vessels (1 for adsorption and at least 1 for regeneration), and does not have recycle loops. A disadvantage is the high temperature needed for regeneration (350 °C). Zeolites were judged to be the best solution for dehydration of ethanol.

On the site of the Zeolite manufacturer Zhengzhou Gold Mountain Science and Technique Co. Ltd. [54], it was found that the zeolite 3A must be used to get water out of a water/ethanol mixture. In the Brazilian Journal of Chemical Engineering [55], an article was found about water uptake rates of zeolites in a water/ethanol mixture. In their 2.5 cm wide and 76 cm long tube, the residence time was 62 minutes to give a purity of 0,01% water (100 ppm).

The flow rate of the top stream of the distillation column in the process is 158 kg/h (Table 8-14). This results with the residence time in a mass of 164 kg ethanol and water mixture that should be present in the drying column. Since this mixture is 94.28% pure in ethanol, the column contains 9.4 kg of water. The article reported an uptake of water of 0.13 gram of water per gram of solid zeolite, so to get all this water out 72.2 kg of zeolite A3 is needed in the column. In table 8-18 below the volume of the different components in the column are shown:

Table 8-18: Contents of the drying column

Component	Density of component [kg/m^3]	Mass in reactor [kg]	Volume in reactor [m^3]
Ethanol	789	154.8	0.196
Water	1000	9.4	0.009
Zeolite	680	72.2	0.106

The total volume of the column is 0.31 m^3. The height over diameter ratio for the original column is 30.4. In order to keep the same efficiencies in the large columns, this ratio should also be used. For the 0.31 m^3 reactor this means a height of 7.2 meters and a diameter of 0.235 m. Since these columns are very slender, they need proper support.

The column is packed with the zeolites and will be filled batch wise with the ethanol/water mixture. This mixture stays for 62 minutes in the column and after that the 99.99% pure ethanol is taken out to the storage facility. The column is than regenerated by blowing hot air trough it. This air evaporates the water inside the zeolite and makes the zeolite reusable for the next batch. It is assumed that the time to regenerate is double the time of ethanol dehydration, so 2 hours are used for the regeneration time. This means that when 1 column is busy with water extraction 2 columns are regenerated. To be sure to always have a column available, a total of 4 columns will be installed.

The price of a vessel of 7.2 meter high and 0.235 meter wide is 11.8 thousand euro [51]. Four of these columns are needed so that price is 47.4 thousand euro. The cost of the zeolite is €1250 per ton [54] (€1180 for the zeolite and €70 for shipping) and as mentioned above, 72.2 kg of zeolite is needed per column. This means 289 kg of zeolite that cost €361.

The size of a transport truck is estimated to be 16 tons (chapter 12). This means that the storage vessel must contain at least 16 tons to be able to fill one truck. Per hour 149 kg of ethanol will be produced, so it takes a bit more than 4 days to fill one truck. To be on the safe side the vessel is chosen to be able to hold 20 tonnes of ethanol. With the density of ethanol of 789 kg per m^3, this means that the vessel must be 25 m^3 (6 meter long, 2.3 meter in diameter). With [45] the price of this vessel will be €4,600.

All the equipment designed above is summarized in appendix 5-1.

8.6.5 Heat exchangers

For heating the incoming stream, heat exchange in the distillation column, cooling the outgoing streams of the distillation and regeneration of the zeolite heat exchangers are needed. Short calculations were done for the area of the heat exchangers. The largest area seemed to be the reboiler with 44m^2 that would cost around € 50,000. This amount is small compared to the other costs (millions of euros for fermentation and distillation), so it is assumed that € 200,000 for the heat exchangers is needed.

Energy is needed to heat the streams. Using the fibres that are not needed at the small-scale plant can generate a part of the heat, but the rest must be made from the produced ethanol and solar boilers. In table 8-19 below all duties of the heat exchangers is given:

Table 8-19: Duties of heat exchangers for the ethanol producing process

Heat Exchanger	Heating Duty [kW (°C to °C)]	Cooling Duty [kW (°C to °C)]
Ingoing to distillation	134 (35 to 92)	
Reboiler	232 (97)	
Condenser		216(78)
Ethanol cooling		6(87 to 35)
Water cooling		142(97 to 35)
Regeneration	6(350)	
Total	372	364

The first 3 duties followed from the Aspen® simulation, the next 2 followed from the simulation after adding 2 heat exchangers after the distillation column to cool the water and ethanol to 35 °C. The last one is calculated by assuming that the duty needed will be equal to the amount of water evaporated in the zeolite. This amount is 9.4 kg per hour, with a heat of evaporation of 2200 kJ/kg.

8.6.6 Ethanol production for different scenarios

In the worst-case scenario, no fibres are available on the farm and no heat integration is possible. In that case burning ethanol must do the total heating duty. The energy density of ethanol is 25 MJ per kilogram, with an assumed efficiency of 80% of internal energy to heat, this means that 42.9 kg per hour ethanol must be burned. This means that for the worst case scenario 1.2% of the produced ethanol must be burned. Together with an assumed 5% of total production needed for transportation, 4% loss to plant personnel and 10% loss by problems in the plant, 80% of the produced ethanol can be sold, which is 1.1 kton per year.

A more realistic scenario is that by means of heat integration the total water cooling duty can be used to heat the incoming stream (which means that 134 kW less will be needed) and that 140 kW of fibres are still available from the farms (chapter 7). This means that less than 1% of the ethanol is needed for burning. A more realistic estimate of needed ethanol for transportation is 1% (chapter 12), 2% for loss to plant personnel and 6% loss by plant problems, which means 90% of the produced ethanol can be sold which is 1.2 kton per year.

9. Process Control

The process can be divided into three sections: cell disruption, evaporation, and gasification.

9.1. Cell disruption section(V03, A01)

Water buffer storage tank (V03):

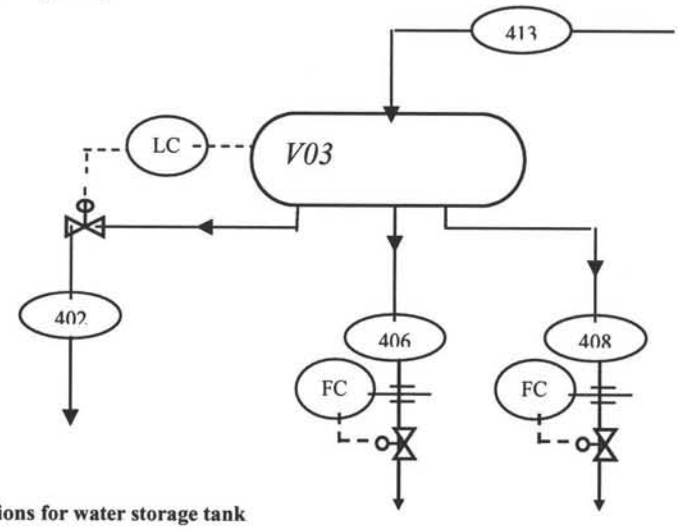

Figure 9-1: Control configurations for water storage tank

It is necessary to control the liquid level in a tank otherwise it will bleed. There is one incoming stream (S413) and three outgoing streams to cell disruption section (S401, 406, 408). Since the amount of water used to wash the grass (S402) is not as critical as the other two (S406, 408), when the liquid level in the tank exceeds the safe level, level controller will detect it and ask the valve in S402 to open. The flow rates of water used in disc refiner (S406) and filter (S408) can be controlled by the flow controllers through comparing with the set point.

Disc refiner (A01):
Flow rate control of disc refiner: It is important to control the flow rate because the amount of grass that enters the disc refiner (S103) is critically set. The flow controller and valve used here are a little different from those used in other sections because the incoming stream is solid. A balance is used as a controller. When the weight of grass is higher/lower than the set point, which means the force put on the balance is higher/lower, the valve will close/open to diminish the disturbance's influence.

9.2. Evaporation section (E01, X05):

Evaporator

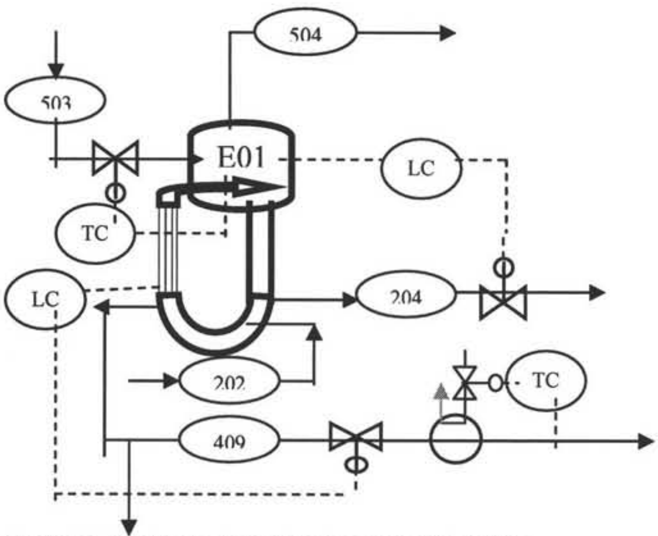

Figure 9-2: Control configurations for evaporator system

Temperature control in the evaporator: It can be controlled by adjusting the flow rate of condensing steam incoming, a temperature controller and a valve are needed.

Liquid level in the coil control: A level controller with a valve in the leaving stream of product (stream number) is used to control the liquid level in the coil. If the level is higher/lower than the set point, the valve will open/close accordingly, which leads to higher/lower flow rate of product stream and level in the evaporator will recover from the disturbance.

At the top of the evaporator, vapor generated (S504) will be reheated in the furnace, then recycled and mixed with the additional raw condensing steam goes through the evaporator.

At the bottom of evaporator, a level controller is necessary to control the level of condensate (water). If the level is higher/lower than the safe line, valve in stream 409, water recycled to the water buffer tank (V03) will open/close. The out let temperature is controlled through controlling the cooling mediate flow rate in heat exchanger E02.

Belt Dryer:

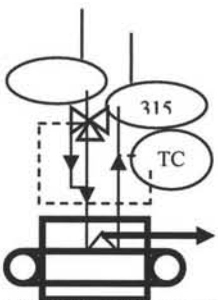

Figure 9-3: Control configurations for Belt Dryer

Temperature control of belt dryer: A temperature controller in the stream of outgoing gas (S315) and a three-way valve can fulfill this task. Heat needed for the dryer is from gas generated in the gasifer (S554). When temperature is higher/ lower than the set point, three-way valve will open/close to release more/less bypass gas stream (S554), mixed with the stream heating in the heat exchanger the temperature will come down/go up.

9.3. Gasification section (R01, T05, R02)

Gasifier

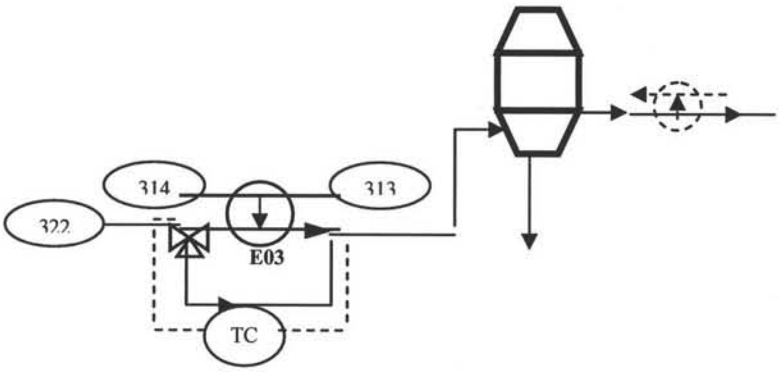

Figure 9-4: Control configurations for gasifier

Temperature and pressure control for gasifier (R01): Gasifier can be obtained as existing machines, which already have control system. Therefore, no extra controller is really needed.
Flow rate control of air incoming (S304 to R01): The flow rate of air needed for gasification is controlled by a temperature controller and a three way valve. When there is a disturbance in the air feed, the flow controller, by comparing with the set point, ask the valve to act. Air is heated in E03, temperature is controlled by the flow rate of gas.
Temperature of air (S304 to R01): Air is heated in E01 by gas generated in gasifier. A temperature controller and a three-way valve are used to control the temperature. The control is same with that of the dryer temperature control above.

Gas Storage and engine

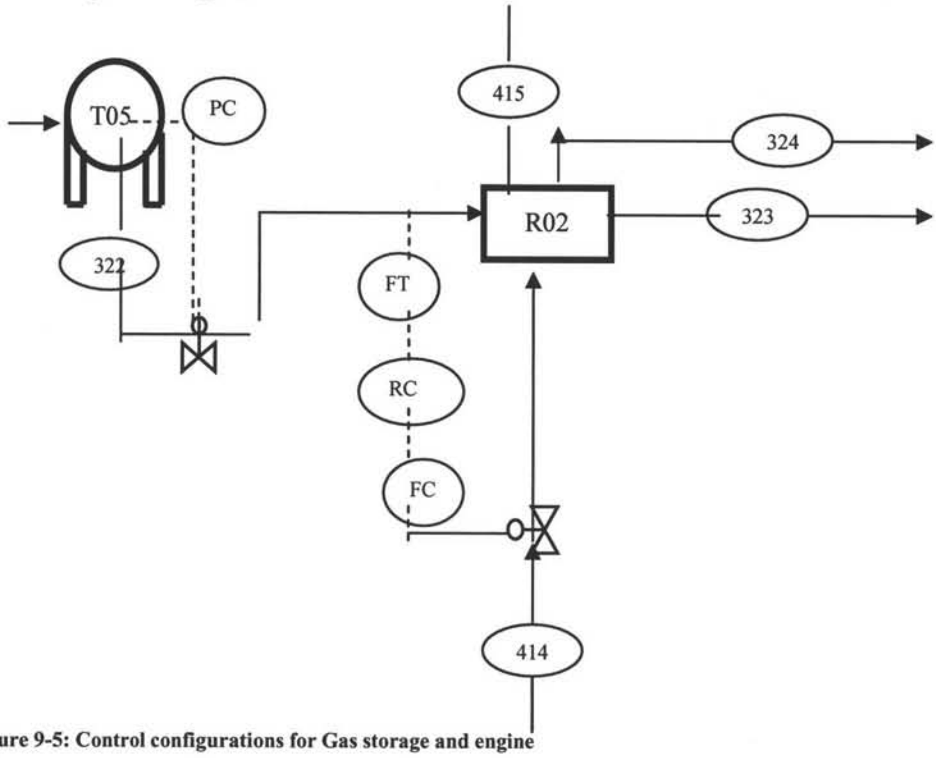

Figure 9-5: Control configurations for Gas storage and engine

Pressure control in gas storage (T05): A pressure controller working together with a valve can complete the controlling. When the pressure in the storage is higher/lower than the set point, the valve in the outlet stream will open/close to release/store more gas to diesel engine and the disturbance can be diminished.

Flow rate control of cooling water used in Gas engine (R02): Cooling water is from the condensate of evaporator (S414) and it will be heated to 100oC after heat exchanging and further used as the condensing steam for evaporator. A ratio controller combined with flow controller (in S411) and transmit unit (in S322) can fulfill this task. The transmit unit will detect the flow rate fluctuation from the gas stream (S322) and transfer it to the ration controller. Comparing with the set point, ration controller will send the signal to the flow controller in cooling water (S323); consequently, the valve acts to adjust the cooling water flow rate. It is necessary that if more gas comes into the engine, more water is needed to cool down the engine and avoid heat loss.

10. Wastes

10.1 Grass processing wastes

To ensure sustainability, elemental balances should be closed. Grass is cut and removed from an ecosystem, taking vital minerals with it. C, H, and O will find it's way back, but other (trace) elements can pose bigger problems. Significant amounts of N, P and K are removed, which somehow need to be returned to the soil. Accumulation of wastes must be avoided.

The fibrous solids in the grass consist mainly of C, H and O. The majority of the other elements is found in the liquid contents part of the cells. This means that, after disc refining and sieving, some 85% of these elements is contained in the protein/sugar stream. These elements will eventually end up in pigs that will excrete part of it as manure, which is returned to the land. A significant part of the elements is assumed to remain in the pigs, and will be exported as meat.

10.1.1 Ashes

The remaining 15% of initial non-CHO elements will enter the gasifier as fibre, but won't transfer to the gas phase. Instead, they become part of the ashes that are removed from the gasifier and the gas filters. This ash, mainly char, is considered to be suitable to return to the land as a fertilizer addition. The minerals contained in them are actually valuable to the land, and lower the cost of fertilizer additives. Considering the possibility of wind (as an example) blowing the ashes away, special care has to be taken in returning.

10.1.2 Off gas

Pyrolysis of the biomass will result in a gas stream, consisting mainly of CO_2, H_2O and N_2, but also amounts of dust, NO_x and SO_x. Proper legislation for the combustion of biomass is currently being developed. To stimulate the use of biomass in the Netherlands, relevant authorities (VROM) have published a circular [1,2] to try to fill any gaps in the current legislation.

When combusting clean biomass to produce electricity (<20 MW_{th}), the following norms are used:

Table 1. Emissions standards for clean biomass combustion (<20MWth)

Pollutant	mg/Nm^3
NO_x	100-200
SO_2	200
Dust	20

The values for NO_x emissions depend on the thermal efficiency of the process used. If a process has 'a yield of at least 40% electricity equivalents', the upper limit of 200 mg/Nm^3 is relevant; at lower efficiencies the limit is 100 mg/Nm^3. Since the used material is freshly grown biomass with a lowered protein (thus N-) content, this biomass can be considered 'clean' biomass. Dusts are filtered out to conform to the norm, and are processed as 'ashes'.

10.1.3 Process water

Any residual water from the feed preparation step will contain only contaminants that were taken out of the soil. As long as there are no other possible contaminants, this water should be returned to the soil, as a part of soil depletion prevention. The quantities of pollutants are not a problem (mass balance), but concentrations could be an issue. Salinization could occur if the water is returned in too high concentrations.

10.2 Ethanol production wastes

During the future ethanol production, new wastes come into play, mainly fermentation by-products. Since the ethanol plant is a future plan only, limited time is spent on thoroughly working out its waste disposal. Instead, the wastes will merely be classified, and their proper disposal will be left for actual plant design.

The following waste streams are to be expected from a 3-farm capacity ethanol plant:

1.15	kton/a unconvertible sugars
2.77	kton/a yeast
35.00	ton/a furfural
35.00	ton/a acetic acid
7.00	ton/a ethanol

An indication of how to dispose of these wastes is divided into three parts: gases, solids and wastewater.

10.2.1 Gaseous streams

During fermentation, a lot of carbon dioxide is formed (1.9kton/a), which needs to be exhausted to avoid pressure build-up. Some organic (by-)products might be entrained within this exhaust, and need to be removed. Thus, the gas should be run through a cooler that condenses most of these organics. Since anaerobic fermentation is required, a classic air-seal based on the exhaust bubbling through a layer of liquid (water) is used, stripping any leftovers. These two steps should sufficiently reduce the amount of non-CO_2 chemicals

10.2.2 Solid wastes

Solid wastes consist mainly of yeast, and, depending of the way the wastewater is treated, an amount of other bio-chemicals. Currently, it is assumed that these solids will be non-toxic, allowing them to be used as pig feed.

10.2.3 Wastewater

Wastewater consists mainly of the bottom stream of the distillation column. It will contain nearly (99.9%+) of the non-ethanol organics, as well as 0.5% of the total ethanol production (7ton/a). The sugar levels in the wastewater will likely lead to entrophy, which means that the water should be treated. This can be done by evaporating the water, which leaves the sugars as solids that can be added to the solid stream. A disadvantage is the likelihood of organics evaporating along with the water. Another option is to have a large water-cleaning tank, where microorganisms are used to reduce the sugar content to acceptable levels. These micro organisms can be added to the solid stream.

11. Risk Management

11.1 Introduction of safety

Safety aspect in the design of a plant relies on the application of various codes and standards of design. These represent the knowledge and experience of both experts and industry. Such application is always supported by the experience of the engineers involved in the plant. In addition, most companies admit to the fact that design personnel are under pressure to keep the project on schedule for a new plant.

In this chapter, safety aspects vis à vis operating are established personnel from a process design point of view by using two tools: Dow Fire and Explosion Index (FEI) assessment and Hazard and Operability study (HAZOP).

11.2 Dow Fire and Explosion Index (FEI)

The Dow Fire and Explosion Index is a very valuable tool in the project design stage, as it makes clear which process units are to be considered as hazardous and where alternative or protective measures have to be considered. It is the most widely used hazard index.

For small-scale process in our project, the most dangerous unit is the gasifier, which operates at very high temperature (up to 660°C) and produce producer gas. The composition of producer gas is 6% water, 24.5% CO, 8% CO_2, 2% CH_4, 20.30% H_2, and 39.2% N_2 [1]. According to Table 11-1, hydrogen has the largest material factor, which is 21, and has a high concentration of it is high. Therefore, the MF = 21 is used for the producer gas.

Table 11-1: Producer gas properties for FEI [2]

Compound	MF	T_d °K	H_C BTU/lb. x 10^3	NFPA Classification			Flash Point °F	Boil Point °F
				N_h	N_f	N_r		
CO	16	1038	4.3	3	3	1	Gas	- 314
CH_4	21	298	21.5	1	4	0	Gas	- 259
H_2	21	301	51.6	0	4	0	Gas	- 422

Gasification has complex reactions, which include oxidation and reduction reactions. Oxidation, or combustion, is described by the following chemical reaction formulae [3]:

$$C + O_2 \leftrightarrow CO_2 \quad -401.9\ kJ/mol$$

$$H + \frac{1}{2}O_2 \leftrightarrow H_2O \quad -241.1\ kJ/mol$$

In the gasifier, the carbon dioxide and water vapour are reduced as much as possible to carbon monoxide, hydrogen and methane, which are the main combustible components of the producer gas.

The most important reactions that take place in the reduction zone of a gasifier between the different gaseous and solid reactants are given below [3].

$C + CO_2 \leftrightarrow 2CO$ +164.9 kJ/mol

$C + H_2O \leftrightarrow CO + H_2$ +122.6 kJ/mol

$CO + H_2 \leftrightarrow CO + H_2O$ +42.3 kJ/mol

$C + 2H_2 \leftrightarrow CH_4$ 0

$CO+3H_2 \leftrightarrow CH_4 + H_2O$ -205.9 kJ/mol

The heat produced by exothermic reactions will be used by endothermic reaction. Therefore, only endothermic reaction will be used in the following analysis of general process hazards.

11.2.1 Solution

The Dow Fire and Explosion Index Analysis is given in appendix 8-1a. The index works out at 110, which is classified as "intermediate". Producer gas is considered to be the most dangerous flammable material in the process. The danger of an internal explosion in the gasifier and storage tank is the main process hazard. The toxicity of producer gas would also need to be considered in a full hazard evaluation.

11.3 Hazard and Operability study (HAZOP)

Hazard and Operability study is a procedure for the systematic, critical, examination of the operability of a process. When applied to a process design or an operating plant, it indicates potential hazards that may arise from deviations from the intended design conditions.

In the small-scale plant, the critical equipment that requires the most attention is reactor R01, the gasifier, because it is operated at a high operating temperature, and the reactions are complex, including endothermic and exothermic reactions. Moreover, producer gas, a flammable substance, is present in the form of producer gas. Appendix 8-1b shows the result of applying HAZOP in the small-scale plant.

For cell breakage and evaporation parts, everything is under control (chapter 9). If the controllers are working properly then they will cause no damage. If some controllers are broken, then they should be replaced to keep the process running safely.

11.3.1 Recommendation

Basically, the main cause of hazard is improper functioning of the valves and controllers. Therefore, in order to keep the process inherently safe, checking these equipments regularly is recommended.

11.4 HAZOP of the fermentor for the large scale process

For the large scale process the fermentor and the distillation column are the 2 pieces of equipment with the highest potential for problems [4]. Since a distillation column is a rather standard piece of equipment, and this distillation column works below 100 degrees and at 1 bar, developing a proper HAZOP for the distillation column it is not a really a challenge. The fermentor works at 1 bar and 35 degrees, so even lower than the distillation column. But, reaction is taking place, and a lot more species are involved. Together with the fact that problems in the fermentor can cause problems in the distillation section it was decided that the fermentor was the unit on which a HAZOP had to be done. In appendix 8-2b the results from a brainstorming session are shown.

11.4.1 Recommendations

From the HAZOP it was found that good control of the process, proper training of the personnel, good storage facilities and handling are the most important aspects to prevent problems [5].

11.4.2 FEI

For the large scale process the fermentation and the distillation column are the most dangerous process unit. The major components in these installations are water, ethanol and CO_2. From these components ethanol and CO_2 have the highest material factor: 16.

The FEI is done for the complete ethanol producing plant, and not only for one of the units. It can be found in appendix 8-2a.

The resulting 123 as FEI means that the process has an intermediate degree of hazard. In order to make this process as safe as possible good control and training of personnel is needed.

12. Logistics

12.1 Transport

12.1.1 Small scale transport

In chapter 3, the decision to design a stationary plant was made. The chapter about equipment design (Chapter 8) confirms the choice, when the sizes of the equipment are taken into account. Because of this choice, a different type of transport is needed; the transport of raw materials and products.

The raw material, legumes, are harvested by hand and are left on the field. From here, the leaves should be transported to the stationary plant. Because an ox is the best-known form of transportation, oxen will do this part of the transport. In the BOD, the calculations for transport were based on trucks, with the assumption that a truck could handle 12 tons of material per drive. An ox can handle around 4 tons per load (an ox can pull two times more than a horse [1], a horse can pull twice his own weight [2], a ox weighs as much as a bull [1] which is 1000 kg [3]). Because this number is based on very strong oxen that are normally fed and walk on smooth ways, the assumption of 4 tons (total) is a little high. For the calculations, 2 tons of grass per ox per load is assumed (the wagon is not taken into account, but it will be an open car made of very light materials).

Per hour, the amount of grass required by the process is 5.62 tons per hour. This means that 3 oxen should arrive per hour for 16 hours at the process to be able to run the process continuously. The disk refiner runs 16 hours a day, but harvesting is only 12 hours a day. This means that if the oxen also work 12 hours a day, more legumes should be delivered per hour. Per hour, 7.5 tons of legumes should be dropped at the plant site. This corresponds to 4 oxen per hour.

The land where the legumes grow is around 15 km^2. Assuming a square, the area is around 4 km by 4 km. Although in the BOD was assumed that the plant was in the middle of the legume field, this will probably not be the case. Figure 12-1 gives the new situation.

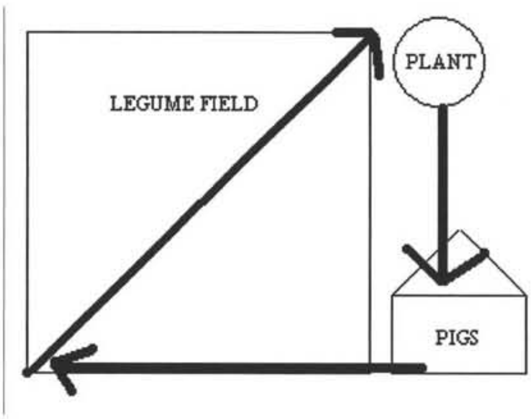

Figure 12-1: A pig farm layout. The Legume field is 4 km by 4 km. The arrows give the longest possible travel distance for 1 ox, which is 14 km.

The longest distance an ox has to travel can be calculated from the figure. First, the legumes should be transported to the plant. The longest distance for this is, the diagonal of the square, around 6 km. Because the oxen should be travel as efficient as possible, the oxen are also used for the transport of protein cakes to the pig farm. The distance between plant and pig farm is assumed to be 4 km. After delivering the protein cakes, the oxen have to go back to the field. If necessary, they can bring the manure from the pigs to the legume field. This last distance will be around 4 km at most. The total round for 1 ox will be 14 km.

Oxen can travel 3.2 km per hour [4]. This means that it will take 4.5 hours for an ox to travel the route. Loading and unloading the wagon is assumed to take 1 hour per route. The total time needed for 1 route is 5.5 hours.

In appendix 9 the Gantt chart for the transport is shown. From this Gantt chart it can be seen that 24 oxen are needed if every ox walks the route twice. If the oxen make three trips, the amount of oxen needed is 16. In the first case, an ox works 10 hours a day with a rest break after the first route of 1 hour. In the second case 15 hours of work is done without any rest in between. In literature is found an ox can work 6 hours a day [5,6]. This is based on logging oxen, where the work is assumed to be heavier than pulling a wagon loaded with grass. So a 10-hour working day with one hour rest in between is best option. Thereby, this scheme is based on maximum distances, so the working day will even be less then 10 hours. The oxen will rest at the pig farm.

First four oxen (1-4) will start walking from field at 6:30 and should arrive at the plant at 7:00 when the disk refiner is started up. These oxen can travel 1.6 km at max, so they come from the nearest field. To get there from the pig farm (where they slept), they have to leave at 5:00.
The second shift of oxen (5-8) will start at the field next to the pig farm. They leave the pig farm at 5:30 to go to the field. There they load the wagon and leave for a walk of one hour to the plant.
The third shift (oxen 9-12) leaves the pig farm at 5:00 to go to the furthest part of the field from the plant (1 hour walk). Then they go to the plant, which is a 2-hour walk.
The fourth shift (oxen 13-16) start half an hour later and walks the same route as shift 3.
The fifth shift (oxen 17-20) will leave the pig farm at 7:00. They go to the field furthest from the pig farm (2 hour walk). From there they only have an hour walk to the plant.
The last shift (oxen 21-24) will leave at 9:00 and go to the middle field. This takes one hour walking. From the field they walk to the plant, which will also take one hour. Afterwards, they go back to the pig farm.

For the second route, all are taken the same; from the pig farm to the far end of the field (seen from the plant) which takes 1 hour, then to the plant (2 hours) and back to the pig farm to sleep. Of course, here also the different parts of the field should be covered, but where the oxen have to go depends on the demand from the field.

12.1.2 Ethanol

The scenario in which ethanol is made from sugar extra transport is needed. Because fuel is available in the form of ethanol and the distances are too far for oxen (20 km or more), this transport will be done with trucks.

The ethanol plant will be situated between three farms. In the BOD the distance between the 60 stationary plants and 1 ethanol plant was assumed to be 172.75 km. In this case only three small plants supply one stationary, the distance is divided by 20. This will give a distance of 10 km. The calculations for the BOD were based on mean distances. In this case, the distance is taken larger to make sure that if something happens with the ethanol production, the farms are not harmed. A safe distance will be 2.5 times the calculated distance, which gives 25 km.

In half a year, more than $11.5*10^3$ ton of sugar-water is produced on the three plants. One truck has a load of 12 ton. Thus, 1000 truckloads are needed per year to transport the sugar-water to the ethanol plant. This corresponds to three trucks (one on every farm) that drive twice per day (in total 100 km per day). The first trip will be around halfway the afternoon (15:30). Second route will be after process shutdown (23:30). The truck can easily drive 25 km in one hour. Unloading the truck will take half an hour. The truck will be back on the farm within three hours.

On the way back, the truck can bring ethanol for the farm if necessary. The total amount of ethanol produced in one year is $1.3*10^3$ ton, so no extra trucks are needed.

The ethanol needed to drive these trucks around can be calculated with the assumption from BOD that 0.16 kg ethanol is needed per km driven. Per year the trucks drive 1000 trips * 50 km per trip giving 50,000 km, which corresponds to 8 tons ethanol. This is only a small amount in comparison to the production of ethanol.

12.2 Marketing Strategy

From chapter 5 information on Zambian agricultural conditions can be extracted to define the market segment that could benefit from the protein cake production plant, i.e. the potential buyers for the process and the product.

12.2.1 Product and Process definition

The options that have been taken into account, given the technical and economic advantages, are the small scale plant for production of protein cakes with 21% of protein content, and production of electricity, which will be used to supply energy for the production of the protein cakes (400 KW) as well as generation of 50 KW which could be used for farms and communications in the surroundings of the plant or sold to neighbour communities.

12.2.2 Alternative products

There is no reference to the existence of plants that extract protein in Zambia. For the product the actual alternatives for protein are imported soybean cakes or concentrates, which have high prices for the farmers. If the process and the product have lower prices, they could be viable substitute for these products.

12.2.3 Market definition

At least 45% of the Zambian population is engaged in agricultural and livestock production. In this context, even when the majority of livestock production is oriented towards cattle and goat raising, pig production is seen as a promissory activity if the prices of the feedstock decrease and better sanitary conditions are implemented. From the total number of farms, 75% percent correspond to poor and very poor farmers with landholdings less than 1 ha, whose production is oriented towards self consumption 23.91% of farmers are in the class of emergent and medium scale, oriented towards subsistence and commercial agriculture, and less than 1% are large scale farmers engaged in commercial agriculture.

12.2.4 Market segment for the process and the product

The small-scale process has capacity to supply protein cakes for 5000 pigs/year. The option for a potential market for the process is a private enterprise, interested in the production of protein cakes, to provide enough feedstuff for 5000 pigs. This private enterprise could be in the sector of processing feedstuffs, or importing feedstuffs.

Considering the product, the amount of protein cakes is enough to feed 5000 pigs. This amount of pigs is not likely to be produced by one farmer due to the requirements of land (1 ha of grass could feed 12 pigs) and capital. The potential beneficiaries of the production of protein cakes and energy are emergent, medium-scale, and large-scale farmers, since they are the ones who can have the amount of land needed and better opportunities of getting finance, (consider that credit conditions are limited and transactions cost are higher). The ideal target could be independent farmers or union of farmers (for instance a union of pig producers), composed by a certain number of emergent or small-scale farmers in a certain region. The product for them could be interesting as an option not to rely in the use of imported feedstock (for instance soy bean cakes), and get cheaper sources of protein.

12.2.5 Marketing strategy

One way of matching production (offer) and consumption (demand) could be agreements in which the private company is the one on charge of carrying out the process for production of the protein cakes, and the potential clients (pig producers) could supply green material, from their land, which will reduce the cost of the feedstuff for pig producers, and also the costs of raw materials for the processor enterprise. This private enterprise could also buy raw materials from other farms (not necessarily pig producers) and sell the product (protein cakes) to landless commercial pig producers. These types of arrangements private company & pig producers could be a type a contract farming, in which case the success of the agreements will depend on the transparency of the negotiations and the bargaining powers of the parts.

With respect to the energy generated, it could be sold to farmers or communities in the surroundings of the processing plant.

12.2.6 Side beneficiaries

Besides the benefits for the development of pig raising activities, there is a side effect of generation of employment (for the process, the labour for grass crops, and labour for pig raising). The labour requirement for grass maintenance and harvest is very high, and labour availability is limited, given that the potential workers are small farmers engaged in subsistence agriculture. Hence, the wage levels of the workers should be high enough to make the option of working in grass fields attractive enough to devote time to these activities.

13. Future potential

13.1 China

13.1.1 General

China has a population of 1,286,975,468 (July 2003 est.), 329 million are farmers and 350 million people are living in absolute poverty. Labour force is 744 million (2001 est.), and 50% (372 million) is for agriculture. The average worker's wage is 60 Euro per month (appendix 10-2). Total land area of China is 9,326,410[km^2], in which only 13.31% (1,277,355[km^2]) of the land is suitable for cultivation, and 1.2%of permanent land is for crops. Since China has abundance of nature resources, cheap labour, and consumers together with an opened and promising big market, it is very interest to evaluate the feasibility of our processes work in China.

13.1.2 Demand driven

Pork industry
China is one of the countries with the largest pork production and consumption in the world. According to FAO statistics, China exported more than 43 million ton pork in 2001, which is about 47% of the total amount of global pork exportation. However, compare to the developed countries, the product quality and the profits made from the pork industry are hanging behind. Pork market weighs up to 60% of the total internal meat product market. With the premise of satisfying the domestic consumption, pork industry aims to increase export, although the pork market is currently still an internal one [1]. This situation formed a big potential to develop the pork industry for the sake of high quality and quantity pork production.

Pig feed
In China, all the pig feeds excluding the animal protein feed come from the foodstuff or the crops leftover [2] due to this fact that pigs are mainly fed in the agricultural regions where there are sufficient raw material to make pig feed. Among those various pig feeds, soybean cake is the dominant as the protein feed [3]. But in fact, soybean production is far away not enough both for human food or pig feed and China becomes the net import country of soybean since 1995 till today [4]. Development in livestock farming leads to more import of soybean. Moreover, in 2030, the population of China will achieve 16 hundred million, there will be a demand of about 7.43 hundred million ton of foodstuff. A noticeable thing is that the demand of foodstuff for feed also will increase to 50% of the total foodstuff production at that time, which will push investors to look for other substitutes to replace the soybean cakes [5].

Trend—the utilizing of biomass
Except the protein value of biomass, the energy in biomass can also be converted into electricity (Gasification or Combustion) or bio-fuel (Fermentation). More researches focus on new energy sources' utilize, like gasification process, which abates the lack of electricity in the agriculture area. Considering the industry ecology, the trend of bio-fuel produced from biomass is also a popular develop direction in China.

Evaluation of the processes feasibility
Possibility for the process to be success depends highly on feedstock availability and its freshness, it is better to build up plants near to the raw materials especially in our case we need fresh grass as feedstock. Considering the distribution of raw materials (grass or crop residues), the whole country area is divided into two parts: Pastoral regions and agricultural regions.

13.1.3 Feedstock availability

Feedstock for the process is highly regionalized on account of different soil condition, climate and environmental condition. There are four types of feedstock can be considered in China now: Natural grassland, cultivated grassland, crop residue and legumes (or mixed with grass). It is very important to determine first, what is the domain grass/residue in the local area, is there abundance of feedstock, and which feedstock has more commercial value (more protein content) than others. Then, the distance between two grasslands or two communities is very big in China, transport time and cost must be considered if only the fresh grass is used as feedstock.

1. Natural grassland

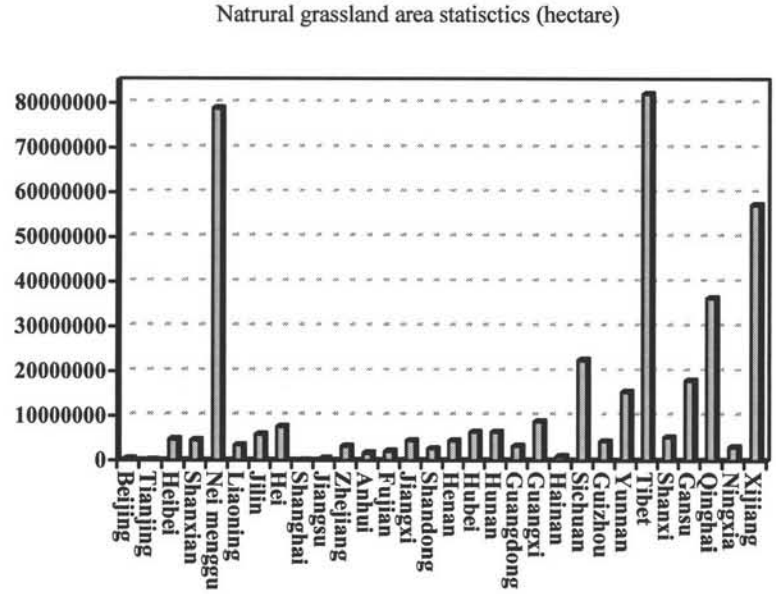

Figure 13-1, Total natural grassland area (hectare) of economic regions in 27 provinces and three big cities of China (This figure is from China Grassland Source Statistics [6,7]

China has grassland about $4 \cdot 10^{13}$ [m^2], which occupies 41.41% of the total land area of China. There is about 84.27% (330,995,458 hectares) of grassland is available for farming. From figure 13-1, the largest grassland is in Inner Mongolia, Tibet, XinJiang and QingHai province. Every province has one of the four biggest pastures in China respectively. The grass output in these grasslands is 75-1050gram/m^2 in average and the main grass species there is gramineous plant (appendix 10-4). There is abundant natural grass before but in recent years, the rapid development of livestock agriculture leads to the long time overgrazing in these pastures, now the government has issued decrees and ordinances to close some farms and forbid grazing on some pastures to protect the grassland resource. The farming there is transferring from grazing to breeding. Therefore, the current natural grass output annually really fluctuates and it is not easy to evaluate whether it is abundant to support the processes for whole China or part of it. But at least, it can supply the process in the local area.

2. Cultivated grass

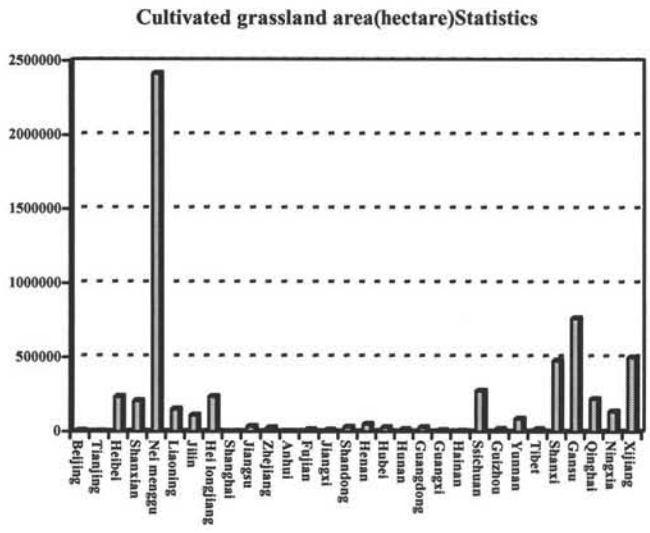

Figure 13-2. Total area of cultivated grassland in China

Currently the total area of cultivated grassland is no more than 2% of the total grassland area in China. From figure 13-2, the main cultivated grassland is in Inner Mongolia province, which holds the second large natural pasture. In agricultural regions, lands are mainly used for cultivation of crops [8] because they are important foodstuff production areas; land for growing the cultivated grass is very limited there.

3.Crop residuals

Currently, the most widely used pig feed are soybean cakes (protein feed) and corn (energy feed) [9]. Crop residuals are abundant in those agricultural regions, about 5 hundred million ton of crop stalk waste produced each year. The disadvantage of the crop residuals is the lower protein content compared with soybean cakes, but if the amount of residuals is enough to make the low quality protein cake and the process can sustain considering the unit capacity, it won't be a real problem. Actually, there already have some successful plants producing low protein pig feed from crop residues in China. See example in Appendix 10-5.

4. Legumes (pure or mixture)

On the natural grassland, legumes are not widely grown because of the environmental conditions, climate, soil and other conditions. For example, in Qinghai province, the proportion of Legume is small (see appendix 10-3); Sedge and the Standing Grain are the predominant grass. The area of Legume is about 4.6%, the Sedge and the Standing Grain is about 90.03%. In cultivated grassland, it is very likely to grow this species of grass but due to the limited usable area, it can only be used as raw material in the regions where it is sufficient for the process. Experts in China have endeavored to research on grass species that have higher quality and production. It can be expected more legumes or its mixtures will be cultivated in China and our process will be promising.
The outcome is the most promising feedstock in different regions is: agricultural regions, crop residual, pastoral regions, and natural grassland.

13.1.4 Process feasibility in different areas

Agricultural regions:

Make some rough calculations of process needed according to the pig farm capacity (appendix 10-1), for example: North China (pig farms distribution are shown in appendix 10-1).

Table 13-1 Amount of pig and process in different sized farms

	1	2	3	4	5	6
Pig farm size	50-90	100-499	500-2999	3000-9999	10000-50000	>50000
Number of pig farms (total China)	703,777	193,450	22,956	2,798	747	16
For Agricultural region 1: North China						
Pig farm distribution	16.5%	15.0%	14.4%	9.0%	8.0%	27.3%
Number of pigs	8128624	8705250	5959195	1636830	1792800	>1792800
Amount of small process needed	1625	1741	1190	327	358	> 358
Amount of large process needed	27	29	20	5	6	> 6

From table 13-1, in North China, for farms ranged above 5000 pigs, the large-scale process can be considered to be feasible in the case that one process serves several farms (total amount of pigs can be fed is 30,000). It is not only because the higher profits that ethanol production brought but also normally those big farms are more developed than those small ones, the electricity is easily available. These big farms are probably the main investors of processes.

For the farms ranged 1, 2, 3 (from 50 up to 5000), both of the processes are feasible because it depends more on several factors which needs more investigation, such as electricity provision, the profits ethanol production made, transportation fees, etc. And considering the fact that feedstock there is crop residuals which have very low protein content and almost 94.5% in total amount pigs are fed there, it is mostly likely that protein cake produced cannot satisfy the farms need. And even if crop residual is sufficient to produce all the protein cakes needed, the units processing capacity in our process will be another problem. However, in pastoral regions, since amount of raw material for producing protein cakes is enough because sufficient raw material supply and much less amount of pigs fed, it is more likely that protein cakes needed in these regions mainly come from pastoral regions and protein cakes produced there can be as the complement feed. If the farms are lack of electricity, obviously small-scale process is more promising. Otherwise, a large-scale process is recommended to make bio-fuel.
Analysis for other agricultural regions: 1, 2, 3, 4, 5 are the same.

Pastoral region

Pastoral region mainly includes the four biggest natural pastures (refer to explanation of Natural grassland). In those natural pastures, the main livestock are ox, cow, horse, camel etc, and very few farms feed pigs. Due to the huge amount natural grass produced per year, large amount of protein cakes can be produced on those pastures more than enough to feed pigs locally and distributed to the pig fed regions such as agricultural regions. Here is another possibility that to transport the grass to the pig fed regions and process grass there instead of on the pastures. But whether the grass can be processed within 12 hours after harvesting is a problem. And the transportation fees for these two materials need more investigation to determine which one is preferred.

Electricity there is very insufficient, for instance, in Tibet [10] about 60% population cannot access to electricity, and in QingHai [11] almost 77.5% family has no electricity supply. Therefore, it is more feasible to make the small-scale process successful in this region. And enough electricity supply can promote local modernization both for the farming and life level of the natives.

13.1.5 Conclusion

It cannot generally define whether a process is possible in the whole China or not because the area is highly regionalized. Both available raw materials and the possibility markets are considered. In different regions of China, what process is feasible depends on the local economy, profits made and electricity provision situation. Here some recommendations are given to different regions: In pastoral regions, small-scale process is advised and in agricultural regions, both small and large scale is feasible.

13.2 The Netherlands

Even though the process is initially designed with developing countries in mind, with Zambia as an example, one should also investigate the potential of a concept for different locations. As an example of a more developed country, the Netherlands is chosen, due to the familiarity of several team members with the country.

13.2.1 General

The Netherlands is 41,500km^2 in size, and has around 16 million inhabitants. The Dutch economy depends heavily on foreign trade, as it functions as a transportation hub for Europe. Inflation was 3.4% in 2002 [12]. Agriculture is an important industry, with relatively few labourers due to its high mechanisation.

13.2.2 The Dutch pig industry

In 2002, the Dutch Central Bureau of Statistics (CBS) [13] counted 11.6 million pigs in the Netherlands. 5 million of these pigs were held in the southern province Noord-Brabant, 2.2 million in Gelderland , and around 1.5 million in both Overijssel and Limburg . The other provinces have much smaller industries. In Zambia, where an area four times the size of the Netherlands holds most of the pigs, fewer pigs are found than in Utrecht (the smallest Dutch province, counting 308,000pigs).

Dutch pig farms with a capacity over 1,000 pigs hold 75% of Dutch pigs; farms with a capacity over 2,500 pigs hold 33%. This means that although the Dutch pig industry is almost 40 times larger than the Zambian industry, most Dutch pigs are held in smaller farms than the ones envisioned in Zambia.

13.2.3 Protein cakes from agricultural waste

The Netherlands is a small, but densely populated country. The land that is not populated is occupied by agriculture. Little room is available for area-intensive industries, and high production/km^2 is required. This makes farmland expensive, and makes it unlikely that cultivating legumes or grass for the production of protein cake is feasible.

However, a large industry produces large amounts of waste. If these wastes (e.g. potato leaf, corn stalks) can be used as feedstock for protein production, and can be obtained at lower prices (since they're not the primary product of the grower), a process similar to the one described in this report could be built. Chance of success depends strongly on feedstock availability (to allow continuous operation), and to a lesser extent on feedstock quality and freshness (the Netherlands is assumed to be small enough for the wastes to be brought to the plant within 10 hours of harvesting).

13.2.4 Process development

A Dutch incarnation of this concept is fundamentally different in all aspects compared to this design: trade-offs can be made between investment cost and operating quality, Dutch infrastructure is more than adequate, labour is expensive.

Firstly, since electricity is easily available, there is no real need to gasify biomass for electricity. This means that other purposes could be found for the fibre. In the Netherlands, many parties occupy themselves in finding options for the use of biomass in production of portable energy carriers. Competing with them while at the same time producing a completely different product (pig feed) seems a bit risky, since a company starting this process would have multiple core objectives (fuel and feed production).

Instead, one could focus on protein production, and be only an intermediary in fuel production. A process is built only to remove the protein out of the biomass. The remaining fibre and sugar can then be sold to companies converting biomass to fuel. Because protein (and thus most of the N) is removed from the fibre, it will likely be a better feedstock for some form of fuel production, compared to other biomass with higher heteroatom content.

Finally, since initial investment cost is less of a problem in the Netherlands, a different approach to creating a process is appropriate. A full-scale plant should be built nearly straightaway, instead of the gradual build-up proposed for Zambia.

14. Economics

In the previous chapters, one scenario is completely worked out and another one is roughly calculated as a future scenario. In order to see the differences between both options in terms of economics, both are calculated. Afterwards, a discussion is given on whether it is possible to implement the future scenario (with ethanol production from sugar) and, if possible based on economics, when to implement the future scenario.

14.1 Total Investment Costs

Economic calculations are based on reference [1]. All calculations used are given in appendix 11-1.

For the utilities, no costs are taken into account. The reason for this is that the utilities used in the process are made within the process; the utilities do not cross the boundaries of the process. The electricity that is not used for the process itself will be sold, making it a product of the process.

The fixed capital costs for the small-scale process are 6.5 million euros. The Total Investment Costs are 8.2 million euros.

14.2 Net Cash Flow Rate

The Net Cash Flow Rate is calculated as the difference between the proceeds and the production Costs. Production costs are costs that are paid every year, for example labour.

The proceeds are given in Table 14-1, the production costs in Table 14-2. It can be seen that the operating costs are much higher then the proceeds, which means that instead of making a profit, an annual loss of € 1.7 million is made.

Table 14-1: Proceeds

	Flow ton/a	Proceeds €/ton	Total proceeds €/a
Protein cakes	2,820	186	523,279
Electricity [kWh]	628,000	0.04	25,120
TOTAL			548,399

Table 14-2: Summary of production costs. Explanations of the numbers are given in appendix 11-2.

			€	€
Variable Costs				
	1	Raw Materials	361,760	
	2	Miscellaneous Materials	39,190	
	3	Utilities	0	
	4	Shipping and packaging	0	
		Subtotal A		400,950
Fixed Costs				
	5	Maintenance	391,902	
	6	Operating Labours	24,300	
	7	Laboratory Costs	4,860	
	8	Supervision	4,860	
	9	Plant overhead	12,150	
	10	Capital Charge	979,755	
	11	Insurance	65,317	
	12	Local Taxes	130,634	
	13	Royalties	65,317	
		Subtotal B		1,679,095
Direct production Costs		A + B		2,080,045
	14	Sales expence	208,005	
	15	General overheads		
	16	Reseach and development		
		Subtotal C		208,005
Annual production costs		A + B + C		2,288,050

Because there is no profit, it is impossible to calculate a Pay Back Time.

Many costs are very important in western countries, but ruin the economics for developing countries. That is why the economics were also calculated in case only the raw materials and the labour are paid for. In that case, a profit of almost € 100,000 is made. This looks more positive, but a Pay Back Time of 85 years (without interest calculations) is found. This is an absurd number, even if a profit is made.

14.3 Economics on Ethanol Production

The future scenario in which ethanol is made from the sugars cannot start if the small-scale scenario is not working. Nonetheless, the economics are calculated for the ethanol scenario.

One ethanol plant can handle the sugar from three farms. All calculations are based on three farms with one ethanol plant. To calculate the Investment costs, costs of the equipment on one farm are multiplied by a factor 3, and the costs of the ethanol plant are added to these costs.

The fixed capital costs for the total ethanol and three farms processes are 12.3 million euros. The Total Investment Costs are 54 million euros.

For the ethanol scenario, the Net Cash Flow Rate is also calculated. The proceeds are given in table 14-3, the production costs in table 14-4. It can be seen that the operating costs are much higher then the proceeds, which means that instead of making profit each year, a loss of € 12.63 million per year is made.

Table 14-3: Proceeds for the ethanol scenario

	Flow ton/a	Proceeds €/ton	Total proceeds €/a
Protein cakes	8,460	186	1,569,838
Electricity [kWh]	1,884,000	0	75,360
Ethanol	1,200	375	450,000
TOTAL			2,095,198

Table 14-4: Summary of production costs. Explanations of the numbers are given in appendix 11-2.

			€	€
Variable Costs				
	1	Raw Materials	1,085,280	
	2	Miscellaneous Materials	258,611	
	3	Utilities	0	
	4	Shipping and packaging	0	
		Subtotal A		1,343,891
Fixed Costs				
	5	Maintenance	2,586,108	
	6	Operating Labours	77,760	
	7	Laboratory Costs	15,552	
	8	Supervision	15,552	
	9	Plant overhead	38,880	
	10	Capital Charge	6,465,270	
	11	Insurance	431,018	
	12	Local Taxes	862,036	
	13	Royalties	431,018	
		Subtotal B		10,923,194
Direct production Costs		A + B		12,267,085
	14	Sales expence		
	15	General overheads	2,453,417	
	16	Reseach and development		
		Subtotal C		2,453,417
Annual production costs		A + B + C		14,720,502

15. Group Process and Creativity

The most important thing learned during these three months is: 'keep trying, never give up so easily'. We trust our own ideas and are not afraid to try something new. Differences in culture, different educational backgrounds and different personalities of members make this group CPD3295 seem very special (compared to other groups). It's not easy to say whether these differences are good or bad, even when they become clearer and clearer over the course of the project. Everybody in this group could tell you stories about what happened, how we dealt with problems and how much we learned from this international collaboration.

15.1 Creativity

Creativity is a tool that merges art and technology together. There are many different methods to work with and it is hard to give proper names to them in the real life. Since our project was only marginally defined, this gave us a lot of (if not too much) space to bring our creativities into play.

Creative project:
Our project itself is a creative idea. Since the contradiction between the lack of foodstuff supply and the increasing demand of pork, people start looking for a method to solve this problem. Not only in Zambia, but also in some other countries, grass is an abundant resource that can be used to produce protein and/or bio-fuel. This idea is quite nice since grass is free in the wild, while it can give out both high values of nutrition (or energy supply) and positive effects of sustainable environmental development.

Creative methods' application in the group:
Brainstorming:
This method is based on searching for information, read literature, known technology and personal experience, combining them in an attempt to generate new and unexpected ideas.
It was mainly in the initial phase of the project. The advantages of it are that it gave us a lot of information and ideas on how to define and work out our project. This information and these ideas were the basis of the process design, following the kick-off meeting. The disadvantage is that too many good and bad ideas come together, which confuses and stagnates our mind, preventing us from making our design direction clear.

Literature and prior knowledge
Literature was used to help us relate to some unfamiliar parts of our design. Previously obtained knowledge was used during our design. Most of the components properties were obtained from tables in the standard handbooks. While nobody knew just exactly how bead mills or zeolites work, but we learned more about them from books and other literature. Especially during the design of equipments, mass and energy balances, most of the calculations are based on knowledge obtained during our studies.

Internet information searching:
We can get nearly infinite amounts of information by using search engines on Internet. Advantages are that it works fast and gives us more than enough information. The disadvantages of it are that it gives us *more* than enough information, and we cannot trust all the information on the Internet. Despite of its speed, quite a lot of time is often spent in searching and judging the required information.

Contact with experts:
Our Principles gave us a lot of advice and comments before we finally finished our BOD report. We aimed to have a meeting with our coach every week. He was helping us to keep our work in a correct direction, and also gave us some good advice whenever we were stuck.

Discussion and Meeting:
We had regular group meetings, both with and without our coach, every week. When necessary, some short meetings or discussions were held outside of the normal schedule. Most meetings were held at the beginning and the end of the project. All key decisions were made during meetings, such as the decisions on scenarios and criteria.

Lunch and coffee time:
Some good ideas come from the relaxed atmosphere. Coffee time is a good chance for us to get to know each other, to make friends, to get the feeling about different cultures together with different languages. It also represents a good opportunity to get a flash idea. Short breaks to have a rest can benefit and increase the working efficiency.

Flexible working time and place:
Some group members cannot work together with others at school often. Some like working at home with music, and some work more efficiently during nighttime than in the daytime. Thanks to the Internet, people can work together without having to be physically present at the same place at the same time. By using FTP programmes, we can log into our working directory at school, download or upload our work instead of having to travel to school to get that file we forgot.

Notes:
Write down suddenly arising ideas; discussing these with other members can yield impressive results

.
Computer tools:
We used Excel functions to simulate our process instead of using Aspen. Some standard symbols can be downloaded from the blackboard, which can be used for drawing the flow sheet scheme with the PowerPoint programme.

15.2 Group process tools

15.2.1 PIQUAR

Determination of the 10 most important criteria
Before the first meeting with the principals (kick-off meeting), the group members picked from the given list with PIQUAR criteria the ones that were useful for this project. Everybody could vote as many criteria as he or she saw fit and all criteria with 4 or more (out of 7) votes was presented at the kick-off meeting to the principals. In the week after the kick-off meeting the principals gave 10 of these criteria a number between 1 (bit important) and 10 (very important). They also could give new criteria and rate those too, which one principal did. One principal rated 11 in stead of 10 criteria, but this does not matter for applying PIQUAR. Two criteria were voted by both principals, so from the original list 19 criteria were left. All team members voted for10 of these criteria with a number between 1 (bit important) to 10 (very important). The resulting list is shown in appendix 12.

To be able to apply PIQUAR 10 criteria must be chosen and ranked. From the 19 criteria left, first the ones with the most votes were chosen (the number of the vote was not taken into account yet),

where the votes of the principals counted double. In appendix 12 it is shown that several criteria had the same amount of votes. In these cases the average numbers of the votes were taken into account. This resulted in the following list of 10 criteria, with the most important one on top, and the least important one of the important ones as last:

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Table 15-1: List of the chosen criteria

	Criterion
A	minimal investment cost
B	trusted by people living nearby
C	low production cost of end product
D	goal of the process must be clear in advance
E	stable operation
F	internal recycling of wastes
G	potential for further developments determined
H	demand driven
I	heat integration
J	based on proven technology

Determination of the weighing factors

In order to make weighing factors for the criteria, a pair-wise comparison matrix must be constructed. This matrix is a reciprocal matrix, meaning that $a_{ij} = 1/a_{ji}$. A number between 1 and 9 must be given, with the following meaning:

1: equal important criteria
3: the criterion in the row has a weak importance over the criterion in the column
5: the criterion in the row is strongly more important than the criterion in the column
7: the criterion in the row is extremely more important than the criterion in the column
9: the criterion in the row is absolutely more important than the criterion in the column

Since it was judged that all chosen criteria were really important and no criterion was extremely more important than any other, no numbers lower than 6 were used in the matrix. The numbers were chosen based on the marks the criteria were given and the total amount of votes. This resulted in the following matrix:

	A	B	C	D	E	F	G	H	I	J
A	1,00	3,00	3,50	4,00	4,00	4,50	5,00	5,50	5,50	6,00
B	0,33	1,00	1,50	2,00	2,50	4,00	4,50	4,50	4,50	5,00
C	0,29	0,67	1,00	1,50	2,00	3,00	3,50	4,00	4,00	4,50
D	0,25	0,50	0,67	1,00	1,50	2,50	3,00	3,50	3,50	4,00
E	0,25	0,40	0,50	0,67	1,00	2,50	3,00	3,50	3,50	4,00
F	0,22	0,25	0,40	0,40	0,40	1,00	2,00	2,50	2,50	3,00
G	0,20	0,22	0,33	0,33	0,33	0,50	1,00	2,00	2,00	2,50
H	0,18	0,22	0,29	0,29	0,29	0,40	0,50	1,00	1,50	2,00
I	0,18	0,22	0,29	0,29	0,29	0,40	0,50	0,67	1,00	2,00
J	0,17	0,20	0,25	0,25	0,25	0,33	0,40	0,50	0,50	1,00

In order to get the weighing factors from this matrix, the eigenvalues and eigenvectors are needed. This was done with the help of the program MatLab ®.The command [eigenvalues, eigenvectors] = eig(A) was given, which returned the eigenvectors of the matrix with the corresponding eigenvalues. From the 10 eigenvalues, only 1 was close to 1, which meant that the eigenvector corresponding to that eigenvalue contained the information for the weighing factors. Every element in this vector must be divided by the sum of all the elements in the vector. This gave the following weighing factors for the selected 10 criteria:

Table 15-2: Weighing factors for the PIQUAR criteria

	Criterion	Weighing factor
A	minimal investment cost	0,29
B	trusted by people living nearby	0,17
C	low production cost of end product	0,13
D	goal of the process must be clear in advance	0,11
E	stable operation	0,10
F	internal recycling of wastes	0,06
G	potential for further developments determined	0,05
H	demand driven	0,04
I	heat integration	0,03
J	based on proven technology	0,03

An alternative way to get the same result for the weighing factors is to divide every element in every column with the sum of the elements of that column and than take the average of each row.

Applying PIQUAR in the CPD

PIQUAR is used for 2 different reasons during the CPD project. The first one was to evaluate the scenarios that were created during the design; the second was to see the progress in the design and the points that needed more attention.

The use for the evaluation of scenarios is explained in Chapter 2.3. Below is the description how PIQUAR is used during the last weeks of the project.

Using PIQUAR to track the areas that need extra attention

During the start of the design it was encouraged to use PIQUAR. But because of troubles with creating the eigenvectors it was decided that the efforts needed to use PIQUAR did not weighed against the results we could possibly get from it. Later it was found that the troubles with the eigenvectors were the result of 2 equal rows in the matrix. These 2 equal rows were caused by the 2 criteria with equal votes and equal average mark (demand driven and heat integration). This was solved by taking the marks from the principals as more important than the marks of the group members. By doing this, the weighing factors shown above were determined.

In the last remaining weeks of the project the PIQUAR method was used to find areas that needed additional attention. At the end of every week everybody gave his or her mark for every criterion. In figure 15-1 the progress on the 10 criteria in the last 4 weeks is shown.

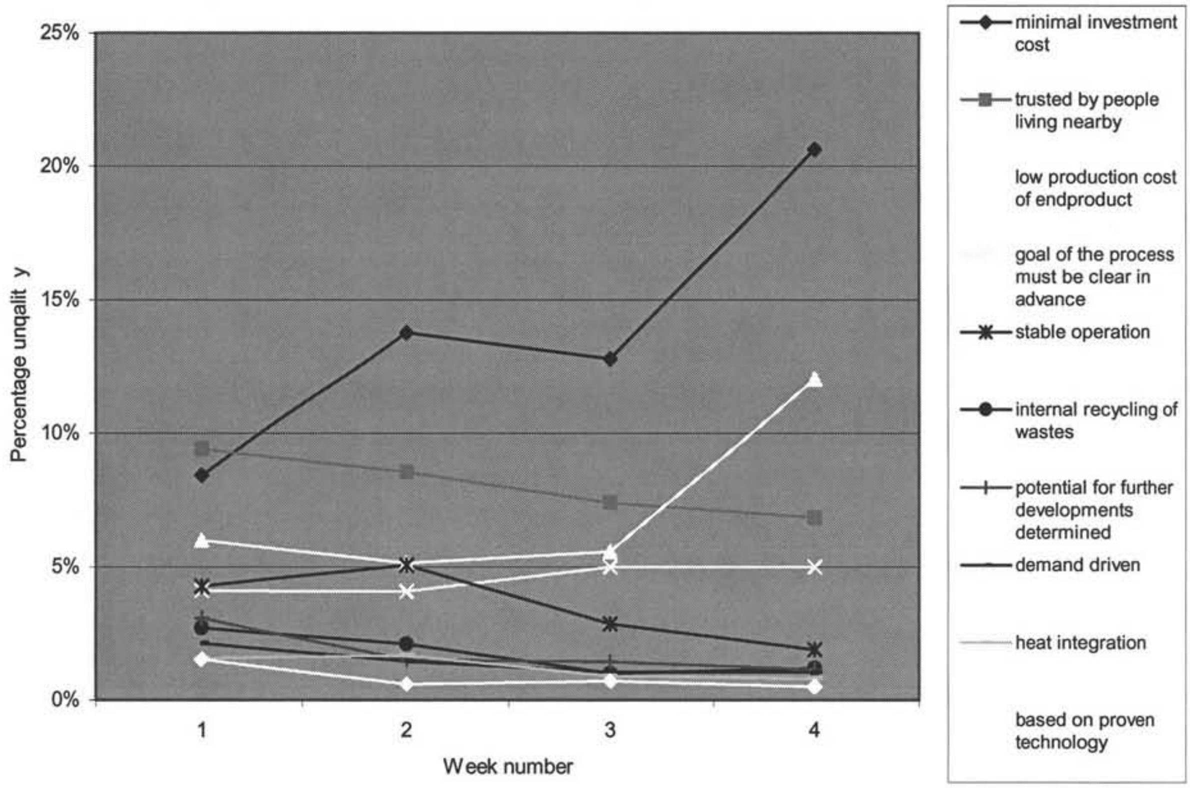

Figure 15-1: Amount of unquality of the PIQUAR factors during the last 4 weeks of the design, week number 1 is 4 weeks before the end of the CPD, week number 4 is the unquality at the end of CPD

As can be seen from the picture, only the 5 criteria with the highest weighting factors seriously contributed to the amount of unquality during the last 4 weeks. From these criteria only that the goal of the process must be known from the beginning is almost constant. This makes sense, because once the project has begun, little can be changed about it anymore.
The criterion about stable operation shows a decreasing unquality, this is due to the fact that during the last few weeks of the design a lot of attention was paid to process control.
The amount of unquality for the criterion about the people in Zambia trusting the process also decreased during the final weeks. The relatively high beginning unquality was because not much attention had been paid to if people would trust certain processes. When talking about this it was agreed upon more and more was agreed that although the Zambians are not as educated as we are, they are not complete Bushmen. They certainly know to operate cars, and most equipment is not very dangerous. The only exceptions are the disc refiner and the gasifier. The first one makes a lot of noise and, although very good washing is ensured, the possibility of a disc breakdown exists. If this breakdown happens in the early stages of the process, the trust in the process will surely decrease. The gasifier is likely to be the less trusted part of the process, although it generates electricity needed for the process and the farm, the high heat and the dangerous gasses produced are something to fear.

The 2 criteria that cause the highest unquality are the 2 criteria related to economy: minimal investment cost and low production cost of end product. These 2 criteria are interlinked, since the investment cost of a process determines also for a part the production cost of the end product. But they are different criteria, since a process with a low investment cost can still have high production costs.

The reason for the high increase in the unquality lies in the fact that the after the final economic calculations the process is economically not feasible, which is explained in the chapter about economics.

In figure 15-2 the quality of the CPD project during the last weeks is shown.

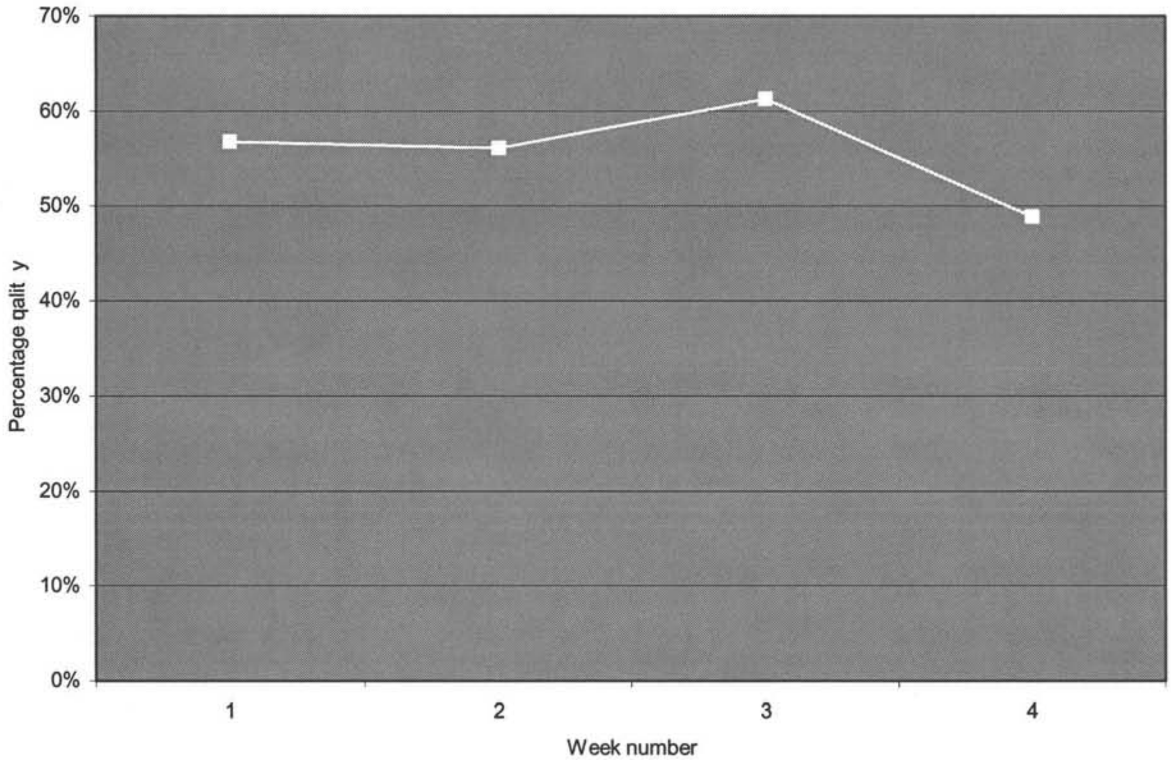

Figure 15-2: Quality of the project during the last 4 weeks of the design

The quality of the design is defined as 100% minus the sum of all unquality percentages. The high decrease of the quality in the last week is due to the economic unfeasibility of the designed process.

15.3 Personal Feelings

In this paragraph, every group member gets the change to express his or her feelings about the project and the group. Also everyone can say for him or her what he/she learned from this project.

15.3.1 Christa

What I learned from this project?
Before I started CPD, I already did a lot of team projects. Most projects were a lot shorter then this one. I also had experience in working with foreign students from all sorts of countries (except European countries). In this perspective I didn't learn a lot except that my prejudice about working with Chinese people was right. Communication is a very difficult thing, especially if you have to talk in another language and you have to deal with cultural differences.

What is my feeling about this project?
Before I started CPD, I really looked up to it. Twelve weeks with a group working 40 hours a week (or even more). When we got the assignment I was surprised because it was not the assignment I expected. I saw forward to start with the project and make something beautiful. Halfway the project, problems came and for one week I wondered if it shouldn't be better to quit. But, after one of the team members did, the project was interesting again from another point of view (could I finish something I didn't like). Now almost at the end of the project, I'm glad it's almost done. In short, although we had some fun, I'm glad it's almost done.

What is my feeling about this group?
A group of 8 persons is really difficult to control, especially if two persons are not present full week. On person quit because he couldn't adapt to the group and couldn't change things his way because he was not there all week. The cultural differences between European people and Chinese people are enormous. Except for a different background in general things, also the background in this field is very different. Communication disorder is the best way to describe our group.

15.3.2 Jeffrey

What I learned from this project?
The most important thing I learned during this project is that cooperating with persons from different backgrounds (cultural, psychological and basic knowledge) is very difficult. I learned much about China and the people living there. Also my communications in English increased quite a lot. Talking with other Dutch people makes talking "English" easy, but when talking with foreigners I was forced to explain more difficult words that I could not translate.
About learning with respect to knowledge, I learned to implement all kinds of courses I had followed earlier during my bachelor phase in one project.
Finally I learned the importance communication. A project of this size and with this many persons is doomed to fail if communication is not handled right. I am not a talker, and my explaining skills are not very good. This was one of the reasons that the BOD's were not the way they were meant to be. During the rest of the design I learned to take time to explain and listen more carefully to other people. This resulted in better understanding and better results.

What is my feeling about this project?
At the moment I was told what the project was about I was very enthusiastic. Not the basic kind of project and a chance to improve the living standards of people that do not have a good life as we have here. The 2 things that scared me a bit were the fact to use a feed for the process which we are not used to as (bio-) chemical engineers, and the fact to make a process that can move. Luckily we were promised people from other studies to help us on these topics. Unfortunately the person who was supposed to be helping with the moving part was not interested in the moving part, but more in chemical processes.
A second fact that made me feel unhappy about this project was that Jenny only joined our group when the first BOD was handed in. As Mr. Petrus said during the second BOD meeting, the feedstock is (one of the) most important aspects in this design. But since we were promised someone who had knowledge in that field, we did not spend much time on it.
Her late joining was another reason the 2 BOD's were not the way they were meant to be, and that gave me a bad feeling about this project.
The last reason for this project for me to feel bad about is that we failed to create an economically feasible project.
Luckily the good feelings about this project are more important to me. Despite of the drawbacks we had and the differences in persons in the group, we managed to create a design. I learned a lot

about communication and the culture of other people, so overall I have a positive feeling about this project.

What is my feeling about this group?
My feelings about this group are mixed. Although I sometimes wondered why some persons were doing this study, I always found out that everyone has his or her values for a group. I think it is healthy to not always like everyone in your group, it keeps you sharp. But in the end I think I can be proud of everyone of us for creating this design as a group together.

15.3.3 Jenny

What I wanted to learn
Through my participation in this cases study I would like to develop my skills in communication and creativity, I have found that my role in a team besides my work is to try to keep harmony in the team, I like to give positive support to the group. I can work with many types of persons and environments, and adapt to different tasks or functions in the group. I also like to give my opinions about how things could be improved. Nevertheless I have found that I like to analyse situations and possible outcomes and sometimes I could take quite conservative positions or follow traditional methods. This could be a limitation because is difficult to develop new ideas. That is one of the reasons I join the group. People backgrounds and the case itself were different from my background and previous experience, hence I saw in this project an opportunity to test my personal qualities and try to diminish my weak points (be more creative and more flexible). I would like to work with this group to have the opportunity to learn how to adapt ideas, and work to the necessities of the team.

What I experienced
So far I have seen that we were very used to work by ourselves and to keep in our minds what was important based on our knowledge. We define the degree of detail and elements to consider based on our experience and knowledge and this could be valuable but could also create problems when the elements considered (degree of detail) deviate from the objectives of the project. I have seen through this work the importance of keeping a clear objective as well as define and keep the limits of the work or better said the scope of the project. I have learn the importance of thinking as a group and adapt my capabilities and knowledge to the necessities of the group, it requires a lot of creativity, patience, flexibility and analysis to get the best outcome. Through this project I have also had the opportunity to see my performance and other team member reactions in situations of crisis. I think this experience has been very valuable, not only for this case but also for future projects for my professional life.

15.3.4 Shanfeng

What I learned from this project?
Taking part in the 2003 Conceptual process design with another 6 students coming from 3 difference countries was for me a great pleasure and a considerable learning experience. In judging how much I learned from the CPD, I believe that basically tow different aspects must be taken into account. The first concerns a learning and applying academic knowledge. As a master student, I learned a lot of academic knowledge from different courses in the first education year. I know I cannot master knowledge well unless I apply them in the real design. The course of conceptual process design gave me a very good chance to apply the knowledge. The second relates working experience in a team. I must say it is very important for me in the future, as a member of a global society.

What is my feeling about this project?
The project our group got is refining the grass to produce protein cake and useful energy, which is more like a biochemical process. I liked it very much at first, because I am learning biochemical engineering. However, later I found it was a very open project, which had many different possibility and choices, and we needed to do a lot of investigation to make a suitable design for Zambia. During this period we had some difficulty in designing. Luckily, with the help of supervisor, Mr. Swinkels, we made a right choice (small-scale process) to continue designing. After overcoming the difficulty, we designed the process step by step and every step was finished successfully. In the end, I found I used most of the knowledge I studied in the first education year, such as process control, chemical risk management, thermodynamic, etc. And I believe I can master them better.

What is my feeling about this group?
This team comprises members with different specialties, coming from different countries and therefore, having different cultural backgrounds. The communication was the most serious problem in the beginning. Communicating in a language foreign to all of us was working not well together. It was one of the reasons why the BOD report was not satisfying twice. The situation was even worse that some of us wanted to quit this team. Later on, we found that complaining and giving up was not useful and wise. We needed overcome the difficult and find a good way to work together. Thanks to Mr. Swinkels, he gave the team a lot of encourages and suggestions. We changed a lot in working way, such as starting to use AAA to divide the task, one Dutch and one Chinese working together, and so on. Everybody tried their best to cooperate with the others. As the time pass by, it seemed that communication was not a very big problem any more. We can work together efficiently and happily. Finally, the project was finished successfully. It proves that people of varying backgrounds, cultures, and language can work well together for a common cause to create a "win-win situation" – one in which everybody benefits.

15.3.5 Shengbin

What is my feeling about the project?
In this cases study I would like to improve the knowledge level of my major and to enhance my communication skills. The project is very open that a lot of possibilities have to be considered carefully at the starting stage. More space is provided to develop my creativity, which is my weak point because sometimes I cannot generate some new ideas and to avoid making mistakes I prefer to follow the traditional ways. On one hand it provides me more opportunities to learn new knowledge that I am not familiar with to broad my view, but for a three-month project, it requires more efforts and time input to make myself understand those knowledge before starting the real design. As a student of Biochemical Engineering, I think a project with a well-defined scope and contains more technique elements is more suitable for me to get more experience to design a real chemical or biochemical process.

What is my feeling about the group?
This group is quite different with those I ever worked with, different backgrounds both educational and cultural. I regard it as a good opportunity to adapt to different situation and different people and keep in mind to think as a group. In this group, what empress me most are the different thinking way of my group members and their creativities. And it really took me some time to accommodate to it and give the input intelligently and efficiently. That is mainly originated from the different education what I received in China because we focused more theory study but without sufficient practice experience. And I saw my group members performance when some unexpected problems came up and I learned to consider in a positive way and to

diminish the negative factors. I think working experience in this group is very valuable for my future study and working in an international group.

15.3.6 Tiany

What I learned from this project?
I seldom did team work before I join this CPD group. I learned how to work with different people and different background. I learned much more knowledge in three months during the design which normally will cost me more than half year to do. I learned how to face the challenges and how to solve the difficulties. I also learned lot abilities such as how to manage my time to do more work, how to switch my role between my task and my life. Yes, I learned a lot of things that will really benefit me in my future professional life.

What is my feeling about this project?
The idea of this project is very attractive for me. I like it because it looks more like a really project in the company. When we start I found that it is the one not like I expected before. I once expected a project with more fixed requirements and more information provided. At the beginning a huge amount of different ideas coming from our members, we have to search a lot of information from all kind of directions we were expected to do. This was a hard work and cost a lot of time. I sometime lost my main direction during that period, stopped there and thinking whether it was worth time and energy to do that since we couldn't see any result from it at that time. It's a bit mess and almost killed our project especially when our Principles were not satisfied with our BOD report and one of our members want to quit from the group. Fortunately, we pick up our courage again and keep going and trying. This is important, I think. The fact is, those work we did at the beginning are quite useful for our following design. It's a pity that we have a lot of good ideas at the beginning, but we don't have enough time to work out all of them.

What is my feeling about this group?
To learn how to work with different culture and background people in this group is another intention of me. I found it is difficult to fully understand the exactly meaning of what others were talking or thinking. This is not only because of different languages, but also because of different ways of thinking and different knowledge backgrounds. I always have wishes to work better and better but sometimes I felt my ability was not equal to my ambitions. I am glad that our members are very nice to explain the problem patiently and friendly. This pushes me to keep going with them and work hard with them. I want to say thank you very much to all of them.

15.3.7 Tobias

What I learned from this project?
The most striking thing that I have learned is that the more you try to avoid miscommunication, the more communication fails. International groups like this one are a special situation, because of the risk of fundamental miscommunication. I've found that the cause of miscommunication isn't just language, but a completely different way of processing information. Although everybody worked hard, and delivered useful work, transfer of knowledge was very limited. People had different mental images of process concepts; language just added to the chaos. Because we focused too much on avoiding international miscommunication, communication started failing intra-nationally, which caused enough confusion to start a vicious circle.
Another thing I've learned is to simply choose a responsibility, and force myself to isolate myself once progress of my part becomes threatened in any way.

What is my feeling about this project?

To me, CPD has been the reason to start studying chemistry, and to study it in Delft; the idea of a project to integrate all your resources and knowledge in an academic environment fascinated me from the start.

When the project actually started, the assignment was everything but the expected. At first glance, it was an interesting concept, open and free, with many options to look for challenges. Rather quickly, it became obvious that the freedom was merely fictional; once idealisations and assumptions were not backed up by other references, we went from the challenge of building a multi-disciplinary, multi-purpose plant to the reality of building the equivalent of a submarine in the Sahara.

Having high expectations always leads to disappointment, and I had expected to finally experience the diversity of chemical engineering. Instead, it was yet another international biomass-to-fuel project. Just my luck I guess.

What is my feeling about this group?

The group itself was interesting and refreshing, but didn't work well for me in a working environment. I myself haven't reached a point where I trusted enough in the capabilities of the group to truly concentrate on my own work, scanning through and worrying about the group's delivered work. This left me feeling slightly unsatisfied with progress, and unsatisfied with my work. Nonetheless, whenever push came to shove, we pulled our acts together, and managed to pull through.

16. Conclusion and Recommendations

16.1 Conclusions

By evaluating the scenario and criteria made, the decision was finally made to design a small-scale process that combines protein production with central heat and power production, along with a development plan for a large-scale process in the future. As raw material, legumes were initially chosen of their high protein contents (compare to grass other green plants), and all calculations were based on the components of legume. Since high legume productivity can only be achieved by cultivating, there is nothing we can do other than to accept the high price (€21.28 per ton). For small-scale, $1.62*10^4$ton legumes are converted into $2.68*10^3$ton 20w/w% protein cakes to feed 5000 pigs per year. An initial capital investment of M€8.6 is needed, and yields an annual loss of M€1.5.

The process was deemed to be unfeasible. The raw materials are too expensive to justify the production of a product that has to compete with products that are made from waste of cash crops. Production of protein feed from fresh organic mater might be feasible, but only if there is value in the material from which the protein is extracted. For instance, if all non-CHO elements can be extracted from biomass, without damaging the protein, the heteroatom-free biomass can be used to make high quality fuel, with the protein as a waste stream with value (up to ~600$/ton). A test-facility is currently operated in the Netherlands, and was concluded to be unprofitable due to high labour costs. This leads to the conclusion that a process like this with protein as the primary product, is only feasible in countries with very low labour costs and large agricultural waste streams

The process has been designed to be self-sustaining, supplying itself and surrounding farms and communities with electricity and steam. The controllability was evaluated and improved [See chapter 9]. Process control and safety analyses were performed, to ensure sound operation. The process has a DOW Fire and Explosion Index of 110, which classifies it as an "intermediate" risk. The gasifier is the most hazardous unit of our process, but ample precautions have been developed to reduce the risk associated with the process.

From the view of sustainable development, all process raw materials are coming from the environment, and have to be returned to it. No additional chemical compounds are used in the process. This simplifies waste treatment: apart from gasification products, all wastes are biological products, allowing them to be returned to the harvested fields. The products of gasification are ashes and producer gas. Ash in the form of dust is entrained within the gas, and is removed and added to the other ashes. The ashes contain valuable minerals, and have to be returned to the harvested fields. The producer gas is combusted in an engine, producing CO_2 and H_2O. Catalytic converters are used to remove SO_x and NO_x.

16.2 Recommendations

Several weaknesses of the design exist and of these weaknesses, the financial aspect is the clearest one. But technical and cultural weaknesses also exist. These weaknesses, and recommendations on how to deal with them are described below.

16.2.1 Financial recommendations

As is mentioned in chapter 14 about the economics of the process, the project is a financial nightmare.
One of the reasons for this is that the price for the protein cakes is fixed. The price must not be higher than the current price for important protein (from soy beans from Argentina). But the content of protein in the feed is only about 5%. This means that a lot of processing is done with a stream 20 times bigger than the product stream. The largest amount of this stream consists of water. This results in relatively large and, because of that, expensive equipment. To solve this problem research could be done to greens plants that have higher protein contents, but it is not very likely to find plants with more than double the amount of proteins, since the used legumes are already famous for their high protein content.

If the cost of the feedstock is lowered, for example if waste from food-crops (corn, wheat, potatoes) can be obtained cheaply, margins might increase enough to justify building a process. Another option is to find uses for other parts of the plants; if enough value can be added to dry matter in green leaves by removing protein, the protein can be sold as a relatively valuable by-product. Until then, more value can be obtained from (expensive) farmland by growing crop for food, rather than for feed.

The most expensive part of the process is the combination of the gasifier and the gas engine. Unfortunately it is not possible to save money on this part, because the energy created from it is needed for the process. At this moment in time, the investment costs for energy from sunlight is still more expensive than for a gasifier. So it is recommended to keep a close eye on the research on solar panels. A second possibility is to do research in process units that require less electricity, especially for the disc refiner (unit with the largest load). A possible alternative is to run the disc refiner and a small electricity generator on ethanol produced in the process.

In the design a future scenario is proposed to make ethanol from the sugar fraction in the legumes. But as described in the chapter economics this is also not economically feasible. A solution to this might be to use instead of standard western fermentation a locally used fermentation for beer. This will cause lower amounts of ethanol produced, but saves on investment costs. A second possibility is to make a shorter distillation column, so less trays and less separation. This will lower costs for distillation, but increases costs for the 4 dehydration columns. For a future research it is recommended to make a more detailed design for the ethanol producing plant.

All following recommendations assume that the process is financially possible.

16.2.1 Technical recommendations

Two striking technical weaknesses have been pointed out: The discs of the disc refiner and the complexity of the gasifier/gas engine combination.

The discs of the disc refiner cannot handle sand particles. Since the opening between the discs is small, a sand particle can easily (because of the high force on it) destroy the discs. In the design a wooden storage and an extensive washing step are implemented to prevent sand particles coming trough. But totally sand-free grass cannot be guaranteed. A recommendation could be to have people near the washing belts to search for sand, but this is very labour intensive, dull and ineffective work.

A better solution could lie in the design of the discs. The most important industry (apart from farming) in Zambia is mining, with copper and the most abundant and exported material. The recommendation is to investigate the possibility of remeltable copper alloys for the use in cheap refiner discs. The current discs need to be very strong because of the toughness of wood for which they are normally used. Grass is a lot softer, so less demand is placed on the structural integrity. If there is enough demand for disc refiner, it could likely be profitable to produce cheap, 'throwaway' refiner discs, which can cheaply be recycled, both for those using and producing the discs.

The combination of a gasifier and a gas engine is a new, but proven technology. To be able to operate these machines safely, a basic knowledge of machinery is needed. People need to be educated in the use and maintenance of them. This could cause problems. Recommendations are below in the cultural part of the recommendations.

16.2.3 Cultural recommendations

The most important cultural problem could be that we as a combined Chinese/south American/European design team have overlooked important aspects of Zambian life that could cause problems with implementing this design in Africa. Although action has been taken to prevent this, a recommendation before using this design in Zambia is to first conduct serious market research on Zambia.

Zambia is in the top 10 of poorest countries. A multi-million euro process appears to be a perfect target for robbers, especially if this process is located a bit away from (more densely) populated areas. It is recommended to analyse the safety situation before placing a process somewhere in Zambia. If the situation asks for it, it could be important to hire some armed guards. A better (but unfortunately also extremely utopical) option would be to find these potential thieves and give them a job on the farm. If they do not have to steal for money and if they have a relation with the process it is not likely the process will be subject of robbery.

A much greater problem in Zambia is aids. The life expectancy in Zambia is around 37 years old; the median age is 16 years. This means that if people are to be educated to use and maintain the machinery, one should keep in mind that there is a very realistic chance that those people die before the investment in education is returned. It will cost constant money and time to keep enough people for the process. It is recommended to cooperate with organisations like the UN in the prevention of and education on aids. This cooperation is also needed because if the number of people infected with aids keeps growing at this rate, nobody is willing to invest anything anymore in such a country. The Zambian government is also one of the poorest in the world, so money for a loan needs to come from outside the country.

Social conditions have to be taken into account when considering benefits of the implementation of this process in Zambia. The process is very labour-intensive, which is a fact that could have two outcomes: on the one side a positive effect due to the generation of employment for poor farmers, and on the other there could be a bottleneck for the production if labour is scarce. Labour scarcity could exists since the majority of poor farmers are engaged in self subsistence, which means that working in the fields of grass should be attractive enough to overcome the trade off of the work allocation (own farmer fields vs grass fields). This of course requires that certain conditions (i.e. food security issues) allow the farmers to get food from other sources.

16.2.4 General recommendations

After a precise investigation of the possibilities of feedstock it was found that the chosen legumes result in the exhaustion of the grass. Due to the late time of arrival of an agricultural expert in the group, there was no time for fundamental changes in the process design. Some actions that could be taken to overcome nutrient depletion could be fertilisation with potassium to compensate the negative balances for this element in the soil. For the case of Nitrogen in scenario 1, where N-fixation is 50%, the shortage could be overcome by N-fertilisation. However, N-fertilisation could suppress the legume's capacity for fixing N. In scenario 2 (90% fixation) there is an accumulation of N in the soil, which could also suppress N-fixation, or lead to leaching of N into the soil.

The option recommended in literature for these cases is to use mixed swards (legume & grass) instead of pure legume stands, since the nutrient cycling in these system could be more balanced. There is a build up of Phosphorus in the soil, as can be concluded from the balances. This could be avoided by reducing inorganic fertilisation and/or the amount of manure applied in the fields.

Another weakness is the lack of exact knowledge of the compositions of the feedstock. The reason for this is that the compositions for all kinds of plants are determined for the consumption by (mostly) cows. During the design assumptions are made, but it is recommended for a better design to make more exact (or at least more relevant with respect to consumption by monogastric animals) compositions of different legumes and grasses.

Losses in pig manure are greater when compared to losses from other manure (for instance cattle manure) under the same conditions. Nevertheless, losses could be reduced through good management. For the calculations values of the most common way in which pig manure is treated were used, but it is recommended to investigate other options to treat the manure before application.

List of Symbols

Symbol	Description	*SI Units*
A	Heat transfer area	m^2
C_P	Heat capacity	kJ/kg/k
D	Amount of steam	Kg/s
F	Flow rate	Kg/s
ΔH_R	Reaction enthalpy	kJ/mol
$\Delta Hvap$	Evaporation enthalpy	kJ/mol
T	Temperature	°C (K)
ΔT_{ln}	Mean temperature difference	°C (K)
ΔT	Temperature difference	°C (K)
Q	Amount of heat transferred	KJ
Q	Amount of heat	KJ
Q	Fan volume	m^3/s
U	Heat transfer coefficient	$Kw/m^2/oC$
N_s	Specific speed in pump	
μ	Viscosity	$Nm^{-2}s$
ϕ_v	Flow rate	m^3/s
ΔP	Pressure drop in pump	bar
u	Velocity of air in blower	m/hr
d	Diameter of pipe	m
l	Length of pipe	m
Re	Reynolds number	
ρ_L	Density of the liquid	kg/m^3
ρ_g	Density of the gas	kg/m^3
u	Viscosity of gas through blower	Ns/m^2

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CPD NR 3295
Conceptual Process Design

Process Systems Engineering
DelftChemTech - Faculty of Applied Sciences
Delft University of Technology

Subject

Refining Green Plants to Protein Cakes and other useful products in the African Country Zambia

APPENDIX

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Keywords

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Assignment issued	:	22.09.03
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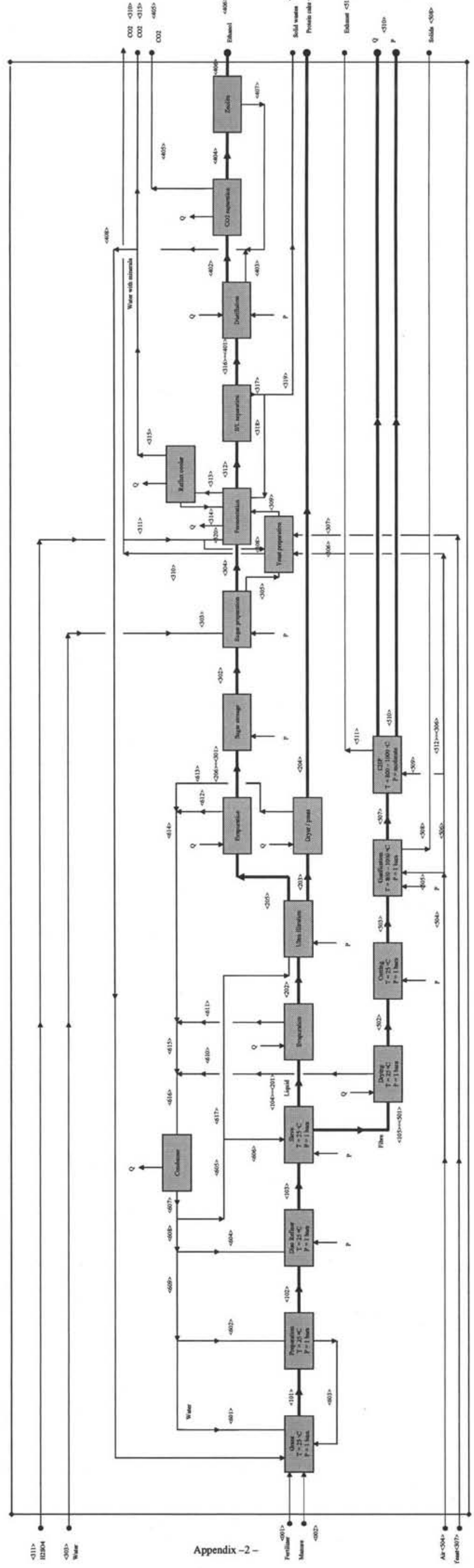
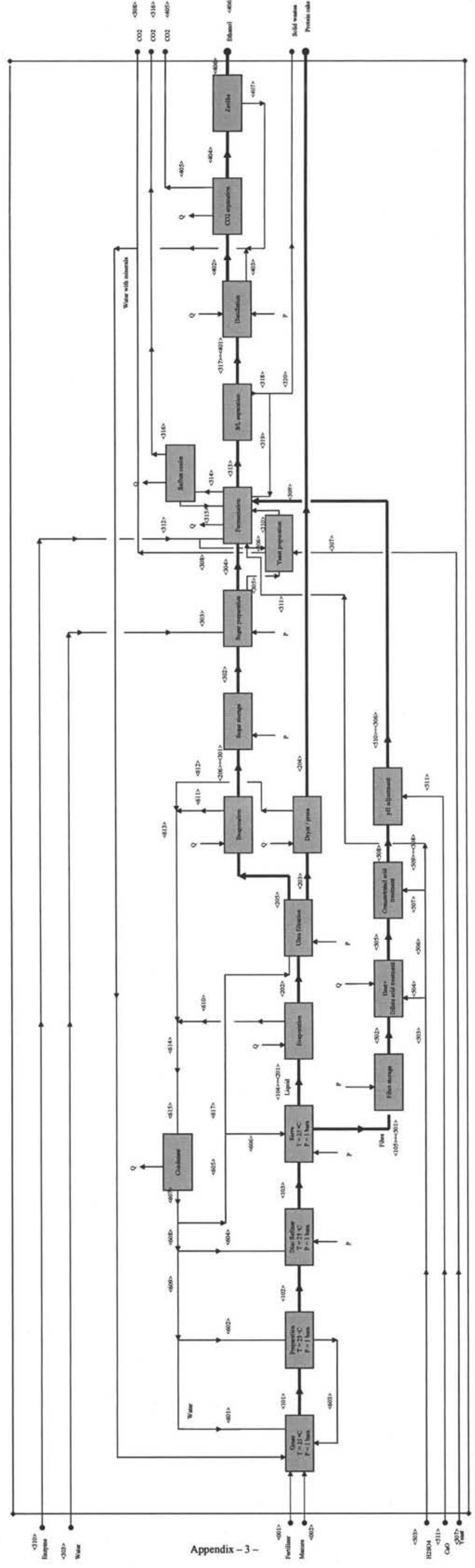
List of Appendices

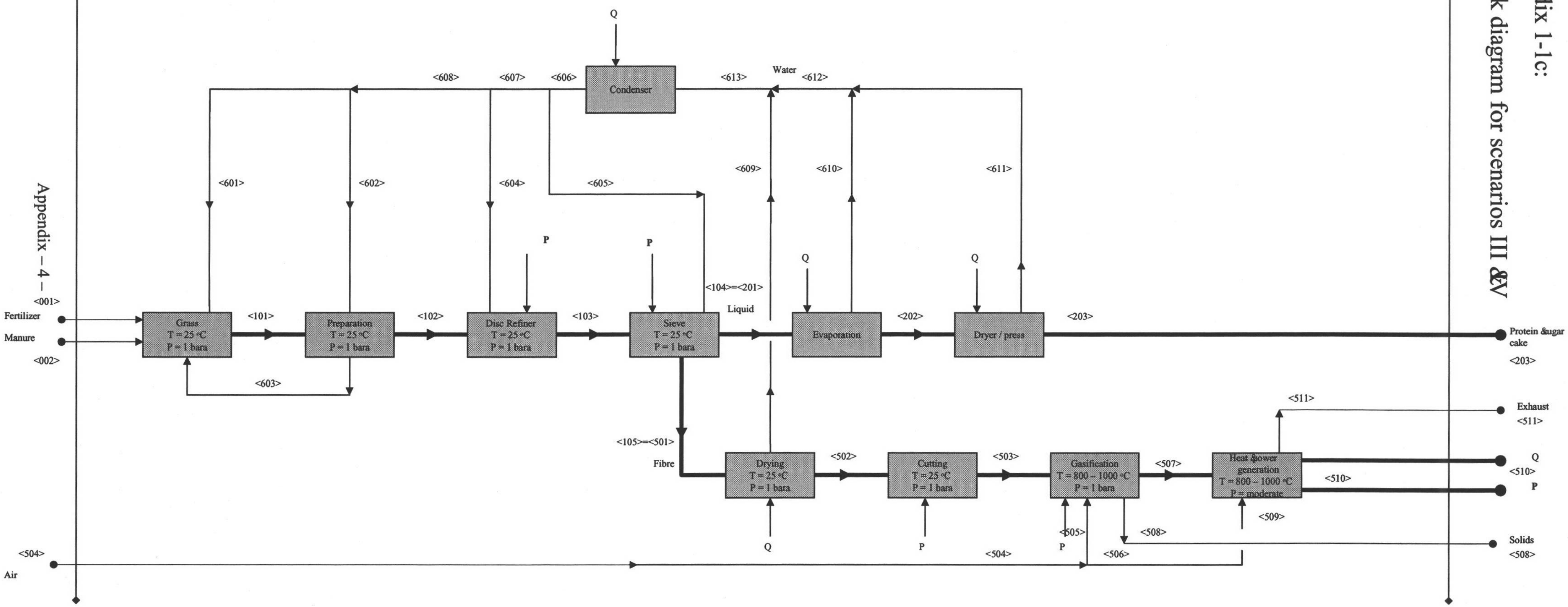
Appendix 1-1a: Block diagram for scenario I



Appendix 1-1b: Block diagram for scenario II



Appendix 1-1c:
Block diagram for scenarios III & V



Appendix 1-2: Margin calculations

Table A1-1: Amounts and prices for rangeland grass

	Stream [ton/a]	Price [EUR/ton]	Total Proceeds [Million EUR/a]
INPUT RANGELAND	3.79E+06	21.46	81.3
Protein cake 86%	4.13E+04	542.27	22.4
Protein cake 8%	4.21E+05	15.00	6.3
Ethanol (sugar)(99.9%)	1.29E+05	345.00	44.4
Ethanol (fiber)(99.9%)	2.04E+05	345.00	70.4
Electricity [MJ instead of ton]	1.06E+09	0.01	10.3
Fibre cake, ox (4% prot)	3.71E+05	15.00	5.6

Table A1-2: Amounts and prices for cultivated grass

INPUT CULTIVATED GRASS	2.34E+06	29.06	67.9
Protein cake 89%	3.99E+04	560.05	22.4
Protein cake 13%	2.82E+05	107.20	30.3
Ethanol (sugar)(99.9%)	7.18E+04	345.00	24.8
Ethanol (fiber)(99.9%)	1.17E+05	345.00	40.4
Electricity [MJ instead of ton]	6.17E+08	0.01	6.0
Fibre cake, ox (4% prot)	2.17E+05	15.00	3.2

Table A1-3: Amounts and prices for legumes

	Stream [ton/a]	Price [EUR/ton]	Total Proceeds [Million EUR/a]
INPUT LEGUME	9.83E+05	21.28	20.9
Protein cake 92%	3.88E+04	575.51	22.3
Protein cake 21%	1.72E+05	185.56	31.9
Ethanol (sugar)(99.9%)	4.16E+04	345.00	14.3
Ethanol (fiber)(99.9%)	6.42E+04	345.00	22.1
Electricity [MJ instead of ton]	3.22E+08	0.01	3.1
Fibre cake, ox (4% prot)	1.13E+05	15.00	1.7

Table A1-4: Amounts and prices for Cultivated grass with legumes

	Stream [ton/a]	Price [EUR/ton]	Total Proceeds [Million EUR/a]
INPUT MIXTURE	1.53E+06	27.44	42.0
Protein cake 92%	3.89E+04	573.98	22.3
Protein cake 20%	1.81E+05	125.95	22.8
Ethanol (sugar)(99.9%)	4.37E+04	345.00	15.1
Ethanol (fiber)(99.9%)	8.42E+04	345.00	29.1
Electricity [MJ instead of ton]	4.43E+08	0.01	4.3
Fibre cake, ox (4% prot)	1.55E+05	15.00	2.3

Appendix 1-3: Scenarios and their margins for different feed stocks

Table A2-1: Different scenarios with their margin (numbers in parenthesis are negative values) (Prices in millions (M€)). Calculations based on mass balances for 300,000 pigs.

Scenario	Grass	Products	In	Out	Margin
A.1	Rangeland grass	Protein low + Ethanol	€ 81.3	€ 76.7	€ (4.5)
A.2	Cultivated grass	Protein low + Ethanol	€ 67.9	€ 70.7	€ 2.8
A.3	Legumes	Protein low + Ethanol	€ 20.9	€ 54.0	€ 33.1
A.4	Mixture legume and grass	Protein low + Ethanol	€ 42.0	€ 51.9	€ 9.9
B.1	Rangeland grass	Protein low + Electricity	€ 81.3	€ 16.6	€ (64.7)
B.2	Cultivated grass	Protein low + Electricity	€ 67.9	€ 36.2	€ (31.7)
B.3	Legumes	Protein low + Electricity	€ 20.9	€ 35.0	€ 14.1
B.4	Mixture legume and grass	Protein low + Electricity	€ 42.0	€ 27.1	€ (14.9)
C.1	Rangeland grass	Protein low + Fibre cake	€ 81.3	€ 11.9	€ (69.4)
C.2	Cultivated grass	Protein low + Fibre cake	€ 67.9	€ 33.5	€ (34.4)
C.3	Legumes	Protein low + Fibre cake	€ 20.9	€ 33.6	€ 12.7
C.4	Mixture legume and grass	Protein low + Fibre cake	€ 42.0	€ 25.1	€ (16.9)
D.1	Rangeland grass	Protein high + Ethanol(sugar) + Ethanol(Fiber)	€ 81.3	€ 137.2	€ 55.9
D.2	Cultivated grass	Protein high + Ethanol(sugar) + Ethanol(Fiber)	€ 67.9	€ 87.6	€ 19.7
D.3	Legumes	Protein high + Ethanol(sugar) + Ethanol(Fiber)	€ 20.9	€ 58.8	€ 37.9
D.4	Mixture legume and grass	Protein high + Ethanol(sugar) + Ethanol(Fiber)	€ 42.0	€ 66.5	€ 24.5
E.1	Rangeland grass	Protein high + Ethanol(sugar) + Electricity	€ 81.3	€ 77.0	€ (4.2)
E.2	Cultivated grass	Protein high + Ethanol(sugar) + Electricity	€ 67.9	€ 53.1	€ (14.8)
E.3	Legumes	Protein high + Ethanol(sugar) + Electricity	€ 20.9	€ 39.8	€ 18.9
E.4	Mixture legume and grass	Protein high + Ethanol(sugar) + Electricity	€ 42.0	€ 41.7	€ (0.3)
F.1	Rangeland grass	Protein high + Ethanol(sugar) + Fibre cake	€ 81.3	€ 72.3	€ (8.9)
F.2	Cultivated grass	Protein high + Ethanol(sugar) + Fibre cake	€ 67.9	€ 50.4	€ (17.5)
F.3	Legumes	Protein high + Ethanol(sugar) + Fibre cake	€ 20.9	€ 38.4	€ 17.4
F.4	Mixture legume and grass	Protein high + Ethanol(sugar) + Fibre cake	€ 42.0	€ 39.7	€ (2.3)

For every scenario (A-F), except scenario D, legumes give higher margin in comparison with the other crops. For scenario D, rangelands give highest margin. This is the result of the high fiber contents in Rangeland grass and the high price for ethanol from fiber.

Because land price is not implemented in the price for the crops, the difference in margin between rangeland and legumes will be less, since almost 8 times more land is needed for rangelands in comparison to legumes for the same amount of proteins. For this reason, Legumes are chosen to be the best option.

From the margins, scenario D gives highest profit. But because the conversion from fibers into ethanol is rather expensive, this may is not the best option.

Margin is not the only criteria a scenario is chosen on. Because in Zambia other criteria are more important, PIQUAR is a better way to choose a scenario.

Appendix 2-1: Pure component properties

Physical properties

Systematic	Formula	Mol. Weight (g/mol)	Phase (room T)	BP[1] (oC)	MP[1] (oC)	FP[1] (oC)	SD kg/m3	LD [2] kg/m3	VD [3]	viscosity[4] uPa.s	solubility in water [5]
Nitrogen	N2	28.013	G	-195.86	-209.95				0.967		Slightly soluble
Oxygen	O2	31.9988	G	183	-219.0			1141.0	1.11		0.05
Carbon	C	14	S	4827	-3550		1800	n.a			
Carbon Monoxide	CO	28.01	G	-191.6	n.a	605		788.6	0.967	16.62	0.0354
Carbon Dioxide	CO2	44.01	G	-78.5	n.a		1562	1032	1.53	13.73	1.7163
Methane	CH4	16.043	G	-161.6	-182.5	-187.78		422.62	0.68	10.28	0.054
ethene	C2H4	28.054	G	-103.7	-169.14	n.a			0.97		26 g/100 mL. Slightly soluble
Ethanol	CH3CH2OH	46.07	L	78.5	-117.3	12.78		789	1.6		
Acetic Acid	CH3COOH	60.053	L	118	17	39		1049	2.1	1.056	miscible
Fufural	C5H4O2	96.086	L	162	-37	60		1159	3.3	1.143	8.3g/100ml
Hydrogen	H2	2.016	G	-252.8	-259			70.973	0.085	3.42	0.0214
Water(room T)	H2O	18	L	100	n.a			1000		0	100
Steam	H2O	18	G		n.a			958.365[6]	0.59	0	100
Glucose	C6H12O6	180.16		118.67	146-150						1.54E-3m3 [7]
Cellulose	(C6H10O5)x	(162.14)x					1.3-1.4				0

Thermodynamic properties

Systematic	Formula	H[8] (kJ/mol)	S[8] (J/mol*K)	G[8] (KJ/mol)	Cp kJ/(mol.K)	Tc (oC)	Pc (bar)	Dc (kg/m3)	Ttr (°C)	Ptr (bar)
Nitrogen	N2	0	191.6	0.0	29.124	-147.0	34.0		63.1	0.1
Oxygen	O2	0	205.1	0.0	29.4	-118.6	50.4	436.1	-218.8	0.0
Carbon	C	0	5.74	0	8.536					
Carbon Monoxide	CO	-110.53	197.658	-137.168	29.141	-140.23	0.349			
Carbon Dioxide	CO2	-393.51	213.783	-394.373	37.135	31	73.825	464	-56.6	5.185
Methane	CH4	-74.6	186.3	-50.5	35.7	-82.7	45.96			
Ethene	C2H4	52.47	219.3	68.4	42.9	9.35	50.6		-169.15	0.0012
Ethanol	CH3CH2OH	-277.6	169.7	-174.8	112.3	240.85	63	6mol/l	-123.15	
Acetic Acid	CH3COOH	-484.3	159.8	-389.9	123.3	592.71	57.86		8.3	n.a
Fufural	C5H4O2	-201.6	n.a	n.a	163.2	657	55.12		n.a	n.a
Hydrogen	H2	0	130.68	0	28.836	-240	12.98	30.09	-259.3	0.072
Water(room T)	H2O(l)	-285.83	69.95	-237.141	75.3	373.98	0.2194			
Steam	H2O(g)	-241.826	188.832	-228.582	33.598					

Notes:

[1] At 101.3 kPa
[2] Density at 25 °C, at 1.013bar
[3] Set air is 1
[4] At 0°C and 1.013bar,
[5] At 0°C,1 atm, vol/volH2O
[6] At 100°C
[7] At 15°C
[8] Enthalpy(H), Entropy(S), Gibbus energy(G) at constant pressure, 298.15K

Symbols:

BP: boiling point
MP:melting point
FP: flash point
SD: solid density
LD: liquid densitu
VD: vapour density
AIT: Auto-ignition temoerature
IT: ignition temparature
LEL: Lower Explosion Limit

Tc	critical temparature
Pc	critical pressure
Dc	critical density
Ttr	triplepoint temperatuer
Ptr	triplepoint pressure
Cp	Heat capacity at cpnstant pressure 1.013bar 298.15K
Cv	Heat capacity at constant volume 1.013bar 298.15K

Pure component Data

Risk management properties[9]

Systematic	Formula	AIT	IT	Flammable Limits	LEL	UEL	LC 50 [9]	MAC Value	LD50 [9]	Chemical Reactivity
		(°C)	(°C)	% by vol in air	%	%		mg/m3		
Nitrogen	N_2	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	Reactions may cause fire or explosion.Gas/air mixtures are explosive.
Oxygen	O_2								n.a	Risk of fire and explosion on contact with combustible materials such as oils or fats.
Carbon	C	n.a	537	n.a	n.a	n.a	n.a	6	n.a	
Carbon Monoxide	CO	608.89	805	12.5-74	12.5	74	n.a	33	n.a	Extremely flammable(NFPS 4),reacts violently with oxgygen difluoride and barium peroxide
Carbon Dioxide	CO_2	n.a	n.a	n.a	n.a	n.a	n.a	9000	n.a	No flammable (NFPS 0)
Methane	CH_4	600	537	5.0-15.0	5	15	n.a	n.a	n.a	Extremely flammable.Gas/air mixtures are explosive.
ethene	C_2H_4	723.16	450	2.7-36.0	2.7	36	n.a	n.a	n.a	Extremely flammable. Gas/air mixtures are explosive.
Ethanol	CH_3CH_2OH	426.67	229.42	3.3-19	4.3	19	n.a	1900	n.a	Highly flammable.Vapour/air mixtures are explosive.
Acetic Acid	CH_3COOH	315.56	157.88	4.0-20	5.4	16	n.a	25		
Fufural	$C_5H_4O_2$	315	316	37671	2.1	19.3	n.a	n,a		
Hydrogen	H_2	400	500-571	4.0-74	4	75	n.a	n.a	n.a	Extremely flammable. Many reactions may cause fire or explosion.Gas/air mixtures are explosive.
Water(room T)	$H_2O(l)$	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	
Steam	$H_2O(g)$	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	

Notes:

[9] It is for human being

Symbols:

AIT: Auto-ignition temoerature

IT: Ignition temparature

LEL: Lower Explosion Limit

UEL: Upper Explosion Limit

LEL: Lower Explosion Limit

Pure Components Properties

Reference *See Reference Chapter 4*

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Appendix 2-2: Ethanol fuel properties

To drive 10000 miles 852 gallons of ethanol are needed [1]. With the density of ethanol this gives 6.23 km per kg of ethanol. The price of ethanol with a high enough purity for the blending with gasoline is 1.03 $ per gallon [8]. This results in a price of €345 per ton. The requirements for the purity are 99.5% pure ethanol, and in the Table A2-1 below are the requirements for the pollutants [9] & [principals]:

Table A2-1: Maximum allowed contaminations in fuel blending ethanol

Component	[ppm]
Water	5000
N	1
S	1
Volatile fatty acids	10
Furfural	100
Non soluble	10
Chloride	<2
Copper	<1
Methanol	200

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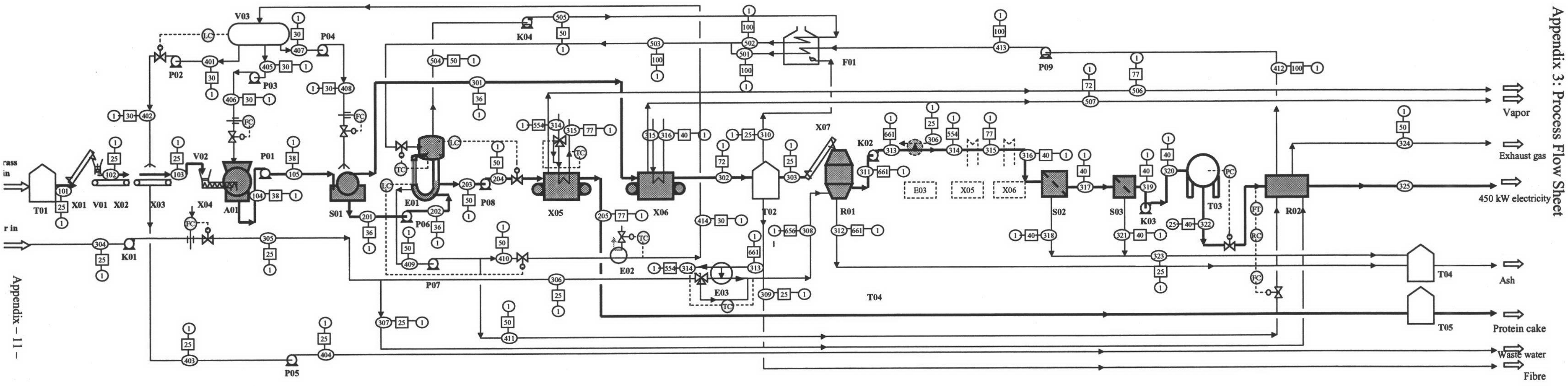
Appendix 3: Process Flow Sheet



Process Equipment Summary

A01 : Disc refiner	K04 : Blower stream 504	P08 : Pump after E01	T02 : Fibre storage after X06	X02 : Transport belt after V01
E01 : Evaporator	P01 : Pump after A01	P09 : Pump stream 415	T03 : Gas storage	X03 : Transport belt after X02
E02 : Condensor below X06	P02 : Pump stream 401	R01 : Gasifier	T04 : Ash storage	X04 : Transport screw
E03 : Heat exchanger below T02	P03 : Pump stream 405	R02 : Gasl engine 450kW	T05 : Protein cake storage	X05 : Belt dryer after E01
F01 : Furnace	P04 : Pump stream 407	S01 : Rotary drum filter after A01	V01 : Hooper and Chopper	X06 : Belt dryer after X05
K01 : Blower stream 304	P05 : Pump stream 403	S02 : Baghouse	V02 : Balance	X07 : Elevator before R01
K02 : Blower after R01	P06 : Pump stream 201	S03 : Cartridge filter	V03 : Recycled water buffer	
K03 : Blower after S04	P07 : Pump stream 409	T01 : Grass storage	X01 : tank Elevator after T01	

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Jeffrey Suijker

Process Flow Scheme

Project : A process to refine green plants – From grass to protein cakes and useful energy source

Proj. ID Number : **CPD3295**

Completion Date : December 15th, 2003

Stream number (oval) — Temp (°C) (square) — Pressure (Bara) (circle)

Appendix 4-1: Mass and heat balances for the process
Appendix 4-2a: Process stream summary. 101-205

4-1a: Overall Mass balances and Heat balances

STREAM Nr. :	101+304	205,309,310,312,323,324,404,506,507	
Name :	all IN	all OUT	all IN - all OUT
COMP	ton/a	ton/a	ton/a
Water		1.80E+04	-1.80E+04
grass	1.62E+04	1.55E+02	1.60E+04
Ash		4.90E+02	-4.90E+02
Protein		5.70E+02	-5.70E+02
Sugar		1.65E+03	-1.65E+03
Fibre		2.56E+02	-2.56E+02
O2	7.04E+03	4.26E+02	6.61E+03
N2	2.32E+04	2.31E+04	3.67E+01
CO			
CO2	1.38E+01	1.74E+03	-1.72E+03
CH4			
H2			
Total flow ton/a	4.64E+04	4.64E+04	0.00E+00
Enthalpy kW	0.00E+00	6.93E+02	-6.93E+02

Appendix 4-2a: Stream summary 101-205

STREAM Nr. :		101,102		103		104,105		201,202		205		203,204	
Name :		grass feed		washed grass		chopped grass		sieved liquid		protein cake		conc. sugar/protein	
COMP		ton/a	kg/s	ton/a	kg/s	ton/a	kg/s	ton/a	kg/s	ton/a	kg/s	ton/a	kg/s
Water				8.08E+02		2.69E+04		3.29E+04		1.34E+02		1.39E+03	
grass		1.62E+04		1.62E+04		2.42E+03				0.00E+00			
Ash						3.65E+02		3.47E+02		3.47E+02		3.47E+02	
Protein						5.92E+02		5.63E+02		5.63E+02		5.63E+02	
Sugar						1.72E+03		1.63E+03		1.63E+03		1.63E+03	
Fibre						1.10E+03				0.00E+00			
Total flow	ton/a	1.62E+04	1.04E+00	1.70E+04	1.09E+00	3.31E+04	2.13E+00	3.54E+04	2.28E+00	2.68E+03	1.72E-01	3.93E+03	2.53E-01
Enthalpy	kW	0.00		0.00		25.40		104.36		22.73		21.08	
phase	L/V/S	S		S/L		L/S		L		S		L	
Press.	bara	1		1		1		1		1		1	
Temp	°C	25		25		37.62		36.21		70		50	

4-1b: Grass processing balances

STREAM Nr. :	101+410	201+302+403+507	
Name :	all in	all out	all in - all out
COMP			
Water	3.15E+04	4.32E+04	-1.17E+04
grass	1.62E+04	6.66E+02	1.55E+04
Ash		3.65E+02	-3.65E+02
Protein		5.92E+02	-5.92E+02
Sugar		1.72E+03	-1.72E+03
Fibre		1.10E+03	-1.10E+03
O2			
N2			
CO			
CO2			
CH4		2.41E+02	-2.41E+02
H2			
Total flow ton/a	4.76E+04	4.79E+04	-2.41E+02
Enthalpy kW	2.12E+02	5.34E+02	-3.22E+02

4.1c: Protein production balances

STREAM Nr. :	201	205+410+506	
Name :	all in	all out	all in - all out
COMP			
Water	3.29E+04	3.29E+04	
grass			
Ash	3.47E+02	3.47E+02	
Protein	5.63E+02	5.63E+02	
Sugar	1.63E+03	1.63E+03	
Fibre			
O2			
N2			
CO			
CO2			
CH4			
H2			
Total flow ton/a	3.54E+04	3.54E+04	0.00E+00
Enthalpy kW	1.04E+02	4.21E+02	-3.16E+02

4-1d: Fibre processing balances

STREAM Nr. :	302+304	309+310+312+323+324	
Name :	all in	all out	all in - all out
COMP			
Water	2.11E+02	6.45E+03	-6.24E+03
grass	6.66E+02	1.55E+02	5.11E+02
Ash	1.83E+01	1.43E+02	-1.25E+02
Protein	2.96E+01	6.90E+00	2.27E+01
Sugar	8.59E+01	2.00E+01	6.59E+01
Fibre	1.10E+03	2.56E+02	8.43E+02
O2	7.04E+03	4.26E+02	6.61E+03
N2	2.32E+04	2.31E+04	3.67E+01
CO			
CO2	1.38E+01	1.74E+03	-1.72E+03
CH4			
H2			
Total flow ton/a	3.23E+04	3.23E+04	0.00E+00
Enthalpy kW	1.82E+01	7.79E+01	-5.97E+01

Appendix 4-2b: Process stream summary, 301-324

Appendix 4-2b: Stream summary, 301-324

STREAM Nr. :	301		302		303		304		305,306	
Name :	sieved solid		dried fibre		fibre to gasifier		air in		gasifier air in	
COMP	ton/a	kg/s	ton/a	kg/s	ton/a	kg/s	ton/a	kg/s	ton/a	kg/s
Water	1.10E+03		2.11E+02		1.62E+02					
grass	2.42E+03		6.66E+02		5.11E+02					
Ash	1.83E+01		1.83E+01		1.40E+01					
Protein	2.96E+01		2.96E+01		2.27E+01					
Sugar	8.59E+01		8.59E+01		6.59E+01					
Fibre	1.10E+03		1.10E+03		8.43E+02					
O2							7.04E+03		5.28E+02	
N2							2.32E+04		1.74E+03	
CO										
CO2							1.38E+01		1.04E+00	
CH4										
H2										
Total flow ton/a	4.75E+03	3.06E-01	2.11E+03	1.36E-01	1.62E+03	1.04E-01	3.02E+04	1.94E+00	2.27E+03	1.46E-01
Enthalpy kw	1.11E+01		18.24		0.00E+00		0.00E+00		0.00E+00	
phase L/V/S	S/L		S		S		G		G	
Press. bara	1		1		1		1		1	
Temp oC	36.21		80		25		25		25	

STREAM Nr. :	307		308		309		310		311,313		312	
Name :	air to engine		preheated air		fibre out		fibre to furnace		producer gas		ash out	
COMP	ton/a	kg/s		0 kg/s	ton/a	kg/s	ton/a	kg/s	ton/a	kg/s	ton/a	kg/s
Water					1.43E+01		3.49E+01		2.25E+02			
grass					4.51E+01		1.10E+02					
Ash					1.24E+00		3.02E+00		8.10E+01		5.77E+01	
Protein					2.00E+00		4.90E+00					
Sugar					5.81E+00		1.42E+01					
Fibre					7.44E+01		1.82E+02					
O2	6.51E+03		5.28E+02									
N2	2.14E+04		1.74E+03						1.70E+03			
CO									8.10E+02			
CO2	1.28E+01		1.04E+00						2.78E+02			
CH4									6.28E+01			
H2									6.71E+02			
Total flow ton/a	2.79E+04	1.80E+00	2.27E+03	1.46E-01	1.43E+02	9.18E-03	3.49E+02	2.24E-02	3.83E+03	2.46E-01	5.77E+01	3.71E-03
Enthalpy kw	0.00		92.99		0.00E+00		0.00E+00		544.82		4.75E+00	
phase L/V/S	G		G		S		S		G		S	
Press. bara	1		1		1		1		1		1	
Temp oC	25		656		25		25		665		665	

STREAM Nr. :	314		315		316		317		318	
Name :	producer gas		producer gas		producer gas		baghouse gas		baghouse ash	
COMP	ton/a	kg/s	ton/a	kg/s	ton/a	kg/s	ton/a	kg/s	ton/a	kg/s
Water	2.25E+02		2.25E+02		2.25E+02		2.25E+02			
grass										
Ash	8.10E+01		8.10E+01		8.10E+01		4.05E+00		7.69E+01	
Protein										
Sugar										
Fibre										
O2										
N2	1.70E+03		1.70E+03		1.70E+03		1.70E+03			
CO	8.10E+02		8.10E+02		8.10E+02		8.10E+02			
CO2	2.78E+02		2.78E+02		2.78E+02		2.78E+02			
CH4	6.28E+01		6.28E+01		6.28E+01		6.28E+01			
H2	6.71E+02		6.71E+02		6.71E+02		6.71E+02			
Total flow ton/a	3.83E+03	2.46E-01	3.83E+03	2.46E-01	3.83E+03	2.46E-01	3.75E+03	2.41E-01	7.69E+01	4.95E-03
Enthalpy kw	450.33		44.27		12.77		12.62		0.15	
phase L/V/S	G		G		G		G		S	
Press. bara	1		1		1		1		1	
Temp oC	554		77		40		40		40	

STREAM Nr. :	319,320		321		322		323		324
Name :	cartridge gas		cartridge ash		gas to engine		ash out		engine exhaust
COMP	ton/a	kg/s	ton/a	kg/s	ton/a	kg/s	ton/a	kg/s	ton/a
Water	2.25E+02				2.25E+02				6.41E+03
grass									
Ash	4.05E-02		4.01E+00		4.05E-02		8.09E+01		4.05E-02
Protein									
Sugar									
Fibre									
O2									4.26E+02
N2	1.70E+03				1.70E+03				2.31E+04
CO	8.10E+02				8.10E+02				
CO2	2.78E+02				2.78E+02				1.74E+03
CH4	6.28E+01				6.28E+01				
H2	6.71E+02				6.71E+02				
Total flow ton/a	3.75E+03	2.41E-01	4.01E+00	2.58E-04	3.75E+03	2.41E-01	8.09E+01	5.20E-03	3.17E+04
Enthalpy kw	12.61		0.01		12.61		0.16		72.99
phase L/V/S	G		S		G		S		G
Press. bara	1		1		25		1		1
Temp oC	40		40		40		40		55

Appendix 4-2c: Stream summary, 401-507

STREAM Nr. :	401,402		403,404		405,406		407,408		409		410		414		411		412,413	
Name :	water-wash		wastewater		water-refiner		water-sieve		condensate		condensate out		water to storage		cold engine coolant		hot engine coolant	
COMP	ton/a	kg/s	ton/a	kg/s	ton/a	kg/s	ton/a	kg/s	ton/a	kg/s	ton/a	kg/s	ton/a	kg/s	ton/a	kg/s	ton/a	
Water	8.28E+03		7.47E+03		1.62E+04		7.05E+03		3.59E+04		3.15E+04		3.15E+04		4.45E+03		4.45E+03	kg/s
grass																		
Ash																		
Protein																		
Sugar																		
Fibre																		
Total flow ton/a	8.28E+03	5.32E-01	7.47E+03	4.80E-01	1.62E+04	1.04E+00	7.05E+03	4.53E-01	3.59E+04	2.31E+00	3.15E+04	2.02E+00	3.15E+04	2.02E+00	4.45E+03	2.86E-01	4.45E+03	
Enthalpy kW	1.11E+01		1.00E+01		2.17E+01		9.47E+00		2.41E+02		2.12E+02		4.23E+01		2.99E+01		89.78603689	5.77E-03
phase L/V/S	L		L		L		L		L		L		L		L		L/V	
Press. bara	1		1		1		1		1		1		1		1		1	
Temp oC	30		30		30		30		50		50		30		50		100	

STREAM Nr. :	501		502		503		504,505		506		507	
Name :	add. steam		rec. steam		comb. steam		evaporate		protein dryer exhaust		fibre dryer exhaust	
COMP	ton/a	kg/s	ton/a	kg/s	ton/a	kg/s	ton/a	kg/s	ton/a	kg/s	ton/a	kg/s
Water	4.45E+03		3.15E+04		3.59E+04		3.15E+04		1.26E+03		2.64E+03	
grass												
Ash												
Protein												
Sugar												
Fibre												
Total flow ton/a	4.45E+03	2.86E-01	3.15E+04	2.02E+00	3.59E+04	2.31E+00	3.15E+04	2.02E+00	1.26E+03	8.09E-02	2.64E+03	1.70E-01
Enthalpy kW	686.47		4852.64		5539.11		4739.34		186.43		401.13	
phase L/V/S	V		V		V		V		V		V	
Press. bara	1		1		1		1		1		1	
Temp °C	100		100		100.00		70.00		50		80	

Appendix 4-3: Parameters nutrient balance

Table A4-1: Parameters used for the calculation of the nutrient balance

Parameter	Value	Unit	Source
Soil			
N available	0.055	%	1
P available	20	ppm	1
K available	0.25	meq/100 gr.	1
Soil density	1.5	g/cc	2
Depth	0.2	m.	Assumption
Fertilisation			
P	22.9	kg./ha/y	1
Legume			
Dry matter yield (wet season)	11300	Kg/ha	
N content	25.6	g / kg	3
P content	1.7	g / kg	4
K content	7.5	g / kg	4
% of litter turnover	30.0	%	5
N from fixation	50 and 90	% from N in the plant	5
Process			
Efficiency recovery in stream	85	%	Process design
Efficiency recovery in extraction	95	%	Process design
Pigs			
# pigs/ha	12.34	Pigs/ha	
N intake	44.2	g/pig/day	6
P intake	18.7	g/pig/day	6
K intake	11.2	g/pig/day	6
N retention (meat)	20.2	g/pig/day	6
P retention (meat)	4.3	g/pig/day	6
K retention (meat)	1.6	g/pig/day	6
N content in slurry	8.75	%	6
P content in slurry	4.27	%	6
K content in slurry	2.81	%	6
N losses in recollection	33	%	7
P losses in recollection	0	%	7
K losses in recollection	24	%	7
N losses in treatment	52	%	8
P losses in treatment	65	%	9
K losses in treatment	35	%	9
Reference 1-9			

References:
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[9] Estimating Manure Nutrients from Livestock and Poultry; Rick Koelsch, Livestock Environmental Engineer; Charles Shapiro, Soil Scientist, Crop Nutrition visited: 21/11/03 http://www.ianr.unl.edu/pubs/wastemgt/g1334.htm

Appendix 5: Equipment design

Appendix 5-1: Equipment Summary

Table A5-1: Storage tanks

Name	Volume [m^3]	Ground area [m^2]	Height [m]	Material of construction	Reference
T01	72	36	2	Wood	Chapter 8.1.1
T02	436	218	2	CS	Chapter 8.1.5
T03	293	------	----	CS	Chapter 8.3.3
T04	100	50	2	CS	Chapter 8.3.4
T05	2400	1225	2	CS	Chapter 8.2.3

Table A5-2: Conveyer Belts

Name	Width [m]	Length [m]	Height [m]	Material of construction	Reference
X01	1	8	4	SS	Chapter 8.1.2
X02	1	3.75	1	SS	Chapter 8.1.2
X03	1	7.5	0.2	SS	Chapter 8.1.2
X04	1	10	5	SS	Chapter 8.1.3
X05	1	12	1	SS	Chapter 8.2.2
X06	3	16	1	SS	Chapter 8.1.5
X07	1	6	3	SS	Chapter 8.3.2

Table A5-3: Apparatuses

Name	Volume [m^3]	Diameter [m]	Height [m]	Reference
A01	------	------	2.5	Chapter 8.1.3
S01	-------	2	5.68 (Length)	Chapter 8.1.4
V01	3	3 (square)	3	Chapter 8.1.2
V02	3	3 (square)	3	Chapter 8.1.3
V03	25	2	8	Chapter 8.3.4

Table A5-4: Heat Exchangers

Name	Surface [m^2]	Reference
E02	23	Chapter 8.4
E03	32	Chapter 8.4

Appendix 5-2: Calculations for the cell disruption steps

Table A5-5: Calculation of the amount of the grass flow rate per minute

Name	Value	Unit
Grass input needed for protein cakes for 5000 pigs	16.2	kton grass per year
Rain season days	180	Day
Hours per day that the machines work	16	hours per day
Grass flow per hour	5.62	ton of grass processed per hour
	60	minutes per hour
	1000	kg per ton
Grass flow per minute	93.6	kg of grass processed per minute
Density of grass cells	1000	kg per m^3
Percentage of grass in the grass flow	50	%
Volumetric flow rate of grass	0.187	m^3 per minute

To produce protein cake for 5000 pigs, 16.2 ton of grass per year is needed. With the above values this gives a volumetric flow rate of 0.187 m^3 per minute.

Table A5-6: Calculation for the belt speed in the 1st washing step

Name	Value	Unit
Volumetric flow rate of grass, Φ_v	0.187	m3 per minute
Grass height, h	0.05	Meter
Belt width, w	1	Meter
Belt speed, v	3.75	meter per minute

Belt speed is calculated with the formula $v = \frac{\Phi_v}{h \cdot w}$. The resulting belt speed is 3.75 m/min.

Table A5-7: Calculation for the belt speed in the 2nd washing step

Name	Value	Unit
Volumetric flow rate of grass	0.187	m3 per minute
Grass height	0.025	meter
Belt width	1	meter
Belt speed	7.50	meter per minute

The same formula as above is used, this time with a grass height of 2.5cm. The result is a belt speed of 7.5 meter. Since a residence time of one minute is chosen, the length of this second washing step should be 7.5 meters.

Table A5-8 summarises where the energy input leaves the disc refiner

Table A5-8: Use of energy in the disc refiner

	[%]	[kW]
Energy input	100	228
Used for cell breaking	33	75
Loss in motor	8	18
Heat produced	59	135

This produced heat is transferred to the process stream. This process stream consists of 5.6 ton grass plus 0.28 ton wash water and 5.6 ton added disc refiner water per hour. This gives a total stream of 11.5 ton per hour, which equals to 3.2 kg per second.

The estimated C_p for this stream is the C_p of water, since more than half is added water, and 72% of the legumes is also water. The C_p of water is 4.2 kJ/(kg K). With the formula: $Q = \phi_{mass} * C_{p,mass} * \Delta T$, this gives a temperature rise of: $\Delta T = Q / (\phi_{mass} * C_{p,mass}) = 135 / (4.2 * 3.2) = 10$ °C. With the surrounding temperature of Zambia of 25 °C this gives a outgoing temperature of the disc refiner of 35 °C.

Table A5-9: Calculation of the amount of solids (grass and fibre) in the stream leaving the disc refiner.

Components	Flow rate [ton/h]
Wash water	0.28
Disc refiner water addition	5.6
Grass	5.6
Total stream	11.5

With the composition of legumes given in chapter 5, and the amount of cell disruption of 85%, the total amount of fibres and intact grass cells is 1.22 ton per hour, which is 10.6% of the total stream.

Appendix 5-3: Filtration options

Table A5-10: Filtration options

	Name	Force	Advantage	Disadvantage	Suitability	Comments
1	Nutsche	Gravity & vacuum	Simplest		-	Not continuous
2	Plate and frame press	Pressure	Oldest, handling viscous liquids and cakes with high resistance		-	Not continuous
3	Leaf filter	Pressure & vacuum	Similar as 2 but lower operating cost	Mechanically remove cake	-	Not continuous
4	Rotary drum filter	Vacuum	Continuous, large throughputs, for free filtering slurries. Low maintenance	Normally need flocculants, low wash efficiency, need agitator	++	
5	Disc filter	Pressure & vacuum	Effective filtering area, cheaper	Cannot use wash water or precoating	-	Washing needed
6	Belt filter	Vacuum	*As disc and rotary drum, but better filtration results	*high capital investment	+/-	Higher capital cost
7	Horizontal pan filter	Vacuum	One machine can automatically execute different filtration functions.		+	High maintenance

* [1] and [2], A belt filter allows 5-20% lower production moisture and 2-10 times the filtration rate of a rotary drum filter, with a wide range of feed size. Low maintenance (5% of installation cost), but has a high capital investment (2-3million€), much higher than disc or rotary drum filter[Ti-DR1]

See also reference [3] and [4]

A comparison of different filters is shown in the table, giving advantages and disadvantages. The rotary drum filter is more suitable for our process design, since it is cheaper, no flocculants are required, and good experiences have been had in its use in biotechnological processes.

References:

[1] http://www.coalage.com/ar/coal_using_belt_vacuum/

[2] Operation of a Disposable Rotary Drum Filter, John Kossik (2001).

[3] Chemical engineering volume 2: Particle Technology & Separation processes, J. M. Coulson, J.F. Richardson, J. R. Backhurst and J. H. Harker, 4th edition (2001), Chapter 7, page 317, Table 7.1.

[4] Chemical engineering volume 6: Chemical Engineering Design, R K Sinnot, 3rd edition (2000), Chapter 10, page 407,Figure 10.10.

Appendix 5-4: (Multi-effect) evaporator design

A5-4a Theory basis **[1]*:***

Assuming liquor has no boiling point rise, and then the heat transmitted per unit time across each effect will be:

$Q_i = U_i A_i \Delta T_i$ ....(eq. A5-1)

Neglecting the heat required to heat the feed, which means heat transferred Q_i in each effect appears as latent heat in the vapor generated and is used as steam in the next effect.

$Q_i = D_i \lambda_i$ ....(eq. A5-2)

And normally, heat transferred areas in each effect are the same, thus

$Q_1 = Q_2 = ... = Q_i$

$U_1 A_1 \Delta T_1 = U_2 A_2 \Delta T_2 = ... = U_i A_i \Delta T_i$

It is commonly the case that the individual effects are alike,

$A_1 = A_2 = ... = A_i$

So that:

$U_1 \Delta T_1 = U_2 \Delta T_2 = ... = U_i \Delta T_i$ ....(eq. A5-3)

From equations above, temperature difference in each effect can be calculated if value of U is set. Combining with heat balance, amount of vapor generated in each stage can be obtained, then deducing heat transfer area from eq A5.1.

But it is very likely that the heat transfer areas calculated from eq. A5-1 are not identical, which is contradictory with the fact that normally they are equal. Therefore, it is necessary to change temperature difference distribution until to get the identical area in all the effect.

A5-4b Method and calculation **[1][2][3]**

1. Effect and feed system determination

The main materials processed in the evaporators are protein/sugar solution. Referred to that in sugar industry 4 to 6 effect are widely used and according to optimization of number of effects from economical view, 4 effects are the most safe and economical option as an initial setting. Protein/sugar solution is heat sensitive, in which protein can be denatured and precipitate with temperature increases. Therefore, it is preferable to run a multi-effect system first (in this case 3 effects), in which no protein precipitates, then following a separate effect for the final stage for protein precipitation. The final product is a concentrated solution of sugar with protein suspension, which can be easily processed in a filter or dryer. After designing a 4-effect system, with the same basis of method, try 3,2-effect system and single stage evaporator respectively. The number of effect can be determined after comparing with these results (heat transfer area, raw steam amount used, etc), combined with consideration of the economic minimization (raw steam cost and equipment investment).

There are three feed system for multi-effect evaporators: forward, backward and parallel. Parallel feed is commonly adopted when crystallization happens during evaporation. It is not suitable for this case. Second, protein will precipitate during temperature range of 50 °C to 80 °C. But at temperature lower than 50°C or higher than 80°C, little amount of protein coagulates. For both feed-forward and feed-backward, it is possible that protein solids travel through each effect until the final one, the situation that always being avoided in a multi-effect system. If make temperature difference in each effect distribute reasonably and no protein precipitate until the final stage, it won't be a problem. Feasibility of these two methods feed type will be compared after determine the effect number.

2. Assumptions [2]:
(1) Assume saturated dry steam at 1 bar (P1), 100°C (T_0) is fed into the heating element of the first effect.
(2) Neglecting boiling point rise in the evaporation.
(3) Estimate heat transfer areas are identical in each effect.
(5) Start program with assumption of same latent heat in each effect, which is dependent on the temperature but actually not too many changes with temperature changes.

3. Calculations for 4-effect and feed-forward system [2]

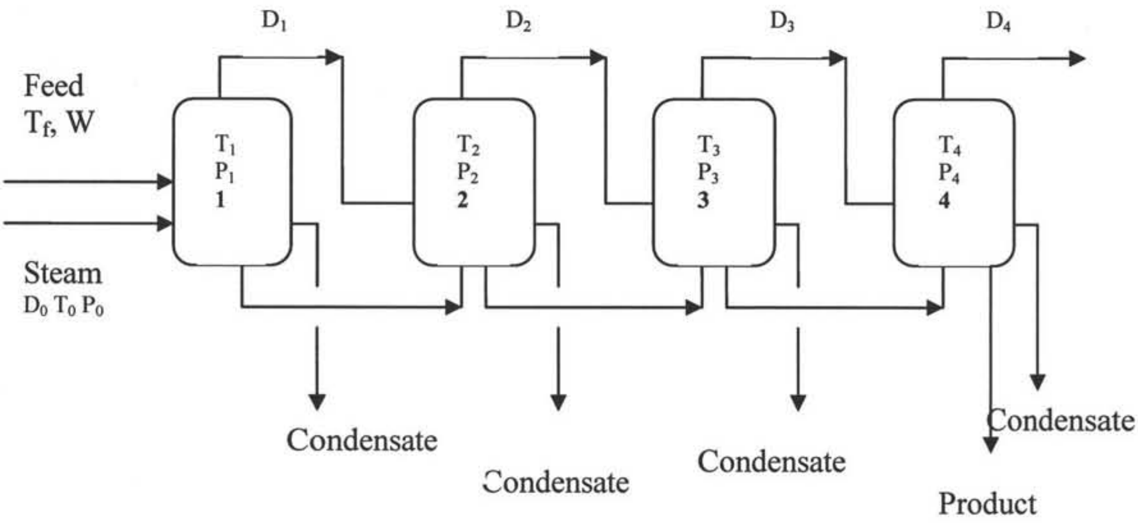


Figure A5-1: Forward-feed arrangement for a four-effect evaporator

1.Set U values
The most concentrated liquor is in the last effect with the lowest temperature, high viscosity, and lowest value of U. U has the tendency that: $U_1 > U_2 > U_3$
Assume U1=3; U2=2.0; U3=1(kw/m²/K)
$\frac{1}{U_1}+\frac{1}{U_2}+\frac{1}{U_3}=\frac{1}{U}$ get $U = 0.545$ KW/m²/K (excluding the final stage where protein precipitates.)

2. Determine temperature distribution in each effect:

To make no protein curd formed before the final effect, set
T_3=80°C T_4=50°C (temperature range at which most of protein will coagulate).
$\Delta T_{total} = T_0 - T_4 = 50$
$\Delta T_4 = T_3 - T_4 = 30$
$\Delta T = \Delta T_1 + \Delta T_2 + \Delta T_3 = T_0 - T_3 = 20$
From heat transfer equation: $Q = UA\Delta T$ (eq. A5-1), get

First effect: $Q_1 = U_1 A_1 \Delta T_1$ where $\Delta T_1 = T_0 - T_1$

Second effect: $Q_2 = U_2 A_2 \Delta T_2$ where $\Delta T_2 = T_1 - T_2$

Third effect: $Q_3 = U_3 A_3 \Delta T_3$ where $\Delta T_3 = T_2 - T_3$

Fourth effect: $Q_4 = U_4 A_4 \Delta T_4$ where $\Delta T_4 = T_3 - T_4$

Form assumptions, and refer to eq. A5-3:

$U_1 \Delta T_2 = U_2 \Delta T_2 = U_3 \Delta T_3 = U \Delta T_{total}$

get:
$$\begin{aligned} \Delta T_1 &= 3.63 & T_1 &= 96.37°C \\ \Delta T_2 &= 5.45 & T_2 &= 90.92°C \\ \Delta T_3 &= 10.92 & T_3 &= 80.02°C \\ \Delta T_4 &= 30 & T_4 &= 50°C \end{aligned}$$

3. Calculate amount of condensing steam needed and vapor generated in each effect

Set $\lambda_0 = \lambda_1 = \lambda_2 = \lambda_3 = \lambda_4$ =2259 KJ/Kg (vapor latent heat at 1 bar, 100°C) [5] as initial value.

From heat balance, for each effect: $Q_{in} = Q_{out}$ combine with eq A5-2:

First effect: $D_0 \lambda_0 = WC_p(T_1 - T_f) + D_1 \lambda_1$

Second effect: $D_1 \lambda_1 + (W - D_1)C_p(T_1 - T_3) = D_2 \lambda_2$

Third effect: $D_2 \lambda_2 + (W - D_1 - D_2)C_p(T_2 - T_3) = D_3 \lambda_3$

Fourth effect: $D_3 \lambda_3 = (W - D_1 - D_2 - D_3)C_p(T_3 - T_4) = D_4 \lambda_4$

Table A5-11: Mass balance over the evaporator

	Solids (Kg/s)	Liquor (Kg/s)	Total (Kg/s)
Feed	0	2.28	2.280
Product	0	0.23	0.23
Evaporation		2.05	2.05

From Table A5-11: amount of water evaporated is 2.05kg/s, giving the following relation:

$D_0 + D_1 + D_2 + D_3 = 2.05$ kg/s

Combine those equations above, 5 unknowns and five equations, D_0, D_1, D_2, D_3, D_4 can be obtained.

4. Calculate heat transfer area.

According to heat transferred equations, combine eq A5-1 and A5-2:

$$A_1 = \frac{D_0 \lambda_0}{U_1 \Delta T_1} \quad A_2 = \frac{D_1 \lambda_1}{U_2 \Delta T_2} \quad A_3 = \frac{D_2 \lambda_2}{U_3 \Delta T_3} \quad A_4 = \frac{D_3 \lambda_3}{U_4 \Delta T_4}$$

If the areas calculated are not identical, which means temperature differences are not correct, it is necessary to change different values for temperature difference until to obtain the equal area. This can be done in a Matlab program. After get nearly same area for each effect, fix latent heat corresponding to the temperature according to the figure below [5], instead of the initial values of all 2259 KJ/Kg. Then run the program again to get more accurate solution for heat transfer and area required, raw steam needed and amount of vapor in each effect. Program for 4-effect system is shown below.

Matlab m. file

```
%Constants%
Cp=4.180; %kJ/kg/K%
W=2.28; %total feed in kg/s%
Ts=373.15;
Tf=306.33;
U1=3; %kw/m2/K%
U2=2;
U3=1;
U4=0.5;%the separate effect%
L0=2259; %kJ/kg 2232.96 %
L1=2330; %2093.4
L2=2360; %2139.92
L3=2380; %2093.4
L4=2500; %2046.88 the fourth evaporator%
%Calculate amount of vapor generated in each effect and ran steam used %
%Adjusting to get identical A %
dT1=5;
dT2=5;
T1=Ts-dT1
dT3=10;
dT4=30;
A=[ L0 -L1        0          0           0;
   0, L1-Cp*dT2,  -L2,        0,           0;
   0, -Cp*dT3    -Cp*dT3+L2, -L3,          0;
   0  -Cp*dT4   -Cp*dT4     -Cp*dT4+L3   -L4;
   0  1           1          1            1];
b=[ W*Cp*(T1-Tf);
  -W*Cp*dT2;
  -W*Cp*dT3;
  -W*Cp*dT4;
  2.05]; %D kg/s,total amount of vapor generated%
D=A\b

%Heat transferred and area required calculation%
A1=D(1)*L0/U1/dT1;
A2=D(2)*L1/U2/dT2;
A3=D(3)*L2/U3/dT3;
A4=D(4)*L3/U4/dT4;
A=[ A1
   A2
   A3
   A4]
Atotal=sum(A)
%heat transferred calculation%
Q1=U1*A1*dT1; %KJ/s%
Q2=U2*A2*dT2;
Q3=U3*A3*dT3;
Q4=U4*A4*dT4;
Q=[ Q1
   Q2
   Q3
   Q4]
```

Result:
As to program of 1,2,3-effect calculations, make some changes in equations and parameters (heat transfer coefficient, temperature difference) correspondingly. Results of those different effect systems are shown in Table A5-12.

```
D = 0.7691
  0.4928
  0.5024                    Atotal = 431.8436
  0.5207                    Q = 1.0e+003 *
  0.5341
A = 115.8300                  1.7374
  114.8280                    1.1483
  118.5632                    1.1856
   82.6224                    1.2393
```

Table A5-12: Results of different effect system [4]

	A(m^2)	Q(KW)				D0(Kg/s)	D(Kg/s)				
	Total	Q1	Q2	Q3	Q4	D0(Kg/s)	Dv	D1	D2	D3	D4
1-effect	35.17	4.79E+03				2.34	2.05				
2-effect	95.30	2.87E+00	2.42E+00			1.27	2.05	1.02	1.03		
3-effect	226.34	2.11E+00	1.57E+00	1.63E+00		0.93	2.05	0.66	0.69	0.70	
4-effect	431.84	1.74E+00	1.15E+00	1.19E+00	1.24E+00	0.77	0.49	0.48	0.50	0.52	0.53

	U(KW/m^2/K)				L(KJ/Kg)					dT			
	U1	U2	U3	U4	L0	L1	L2	L3	L4	dT1	dT2	dT3	dT4
1-effect	3.00				2259.00	2500.00				20.00			
2-effect	3.00	1.70			2259.00	2380.00	2500.00			20.00	30.00		
3-effect	3.00	2.00	0.70		2259.00	2360.00	2380.00	2500.00		9.50	10.50	30.00	
4-effect	3.00	2.00	1.00	0.50	2259.00	2330.00	2360.00	2380.00	2500.00	5.00	5.00	10.00	30.00

That table shows that more effect used, less raw steam needed, and more total heat transfer area needed. One evaporator has the smallest heat transfer area at the expense of largest amount of condensing steam incoming required. But because the steam can be obtained through heat generated in the gasification process without any paying, it is not a real problem if consider the steam cost. And less equipment used, less investment needed. Therefore, one effect is the most suitable one among those different effects system.

A5-4c: Design of a single stage evaporator [2]

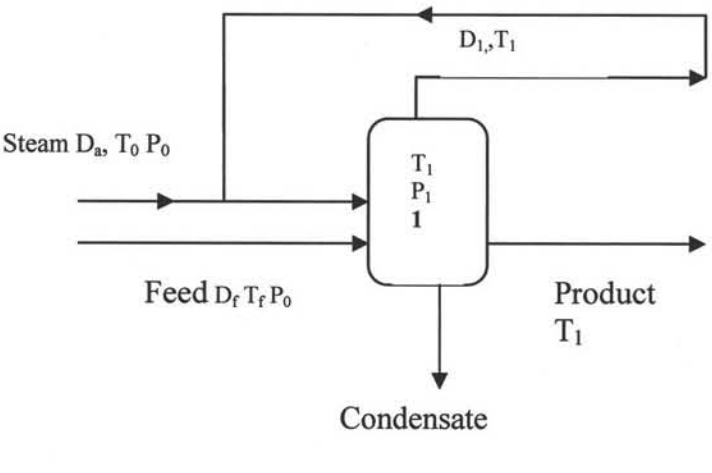


Figure A5-2 Single stage evaporator

The outgoing vapor generated at lower temperature from the solution will be reheated to 100°C and recycled to merge with the additional raw steam, and start the new evaporation.
As known from Table 2, for a single stage:

$$T_0 = 100°C, T_1 = 50°C, D_0 = 2.34kg/s, D_1 = 2.05kg/s, C_p = 4.18kJ/k/kg$$

Additional steam needed: $D_a = D_0 - D_1 = 0.29kg/s$

Q needed to generate this amount of steam:

$$Q = mC_p\Delta T + m\Delta H_{vap}$$

$$Q_a = D_a[C_p(T_0 - T_r) + 2260] = 722.12kw$$ where T_r=25oC (room temperature)

Q needed to heat out steam D1 for the recycle use:

$$Q_{recycle} = mC_p\Delta T = D_1C_p(T_0 - T_1) = 428.45kw$$

Total Q needed: $Q = Q_a + Q_{recycle} = 840.12kw$

Heat transfer in the evaporator (Table A5-12)
Qtotal=4879.40 kw

Price:
Aera=37.81 m^2=378.57ft^2, choose a 400 ft^2 evaporator made of material carbon steel. Total cost: $310900.

Table A5-13: Evaporator summary

Type	Submerged tube	
	Value	Unit
Pressure	1	Bar
Heat load	4879.40	kw
Heat transfer coefficient	3000	$w/m^2/k$
Heat transfer area	35.17	m^2
Condensing steam needed	2.34	Kg/s
Steam generated (recycled)	2.05	Kg/s
Additional steam needed	0.29	Kg/s
Cost	311	k€

Reference:

[1] *J. M Coulson& J F Richardson*, Chemical Engineering, Vol.2, 2001
[2] *J. M Coulson& J F Richardson*, Chemical Engineering, Vol.6, 2001
[3] Seperation Processes
[4] http://www.univ-reims.fr/Externes/AVH/MementoSugar/001.htm
[5] *Robert H. Perry*, Perry's Chemical Handbook, 6th, McGRAW-Hill, 1984
http://www.matche.com/EquipCost/Exchanger.htm

Appendix 5-5: Calculations for the rotary drum filter

The dry matter that should be handled in the design is 0.17 kg solid per second.
In table 7.2 of reference [1], the solid contents goes from 15% to 50%. From this, the amount of water that is taken out the solution can be calculated.

$$\frac{\text{kg dry matter}}{\text{kg dry matter * water}} = w\% \qquad \text{eq. A5-4}$$

Table A5-14: Amount of water by different w% at a dry matter amount of 0.17 kg/s.

w%	Amount of water [kg/s]
15	0.96
50	0.17
67	0.08
90	0.02

For the case in the reference, 0.79 kg water is taken out per second. This is done with a solid handling rate of 0.02 kg dry per second per square meter. The amount of water taken out in the design will be 0.06 kg water per second. With Equation A5-5 the solid handling rate of the design can be calculated.

$$\frac{\text{solid handling rate}_{\text{reference}}}{\text{water release}_{\text{reference}}} * \text{water release}_{\text{design}} = \text{solid handling rate}_{\text{design}} \qquad \text{eq. A5-5}$$

This gives a solid handling rate for the design of 0.0017 kg dry matter per second per square meter. Because it is an estimate, the solid handling rate is stated at 0.002.

References:

[1] Chemical engineering volume 2: Particle Technology & Separation processes, J. M. Coulson, J.F. Richardson, J. R. Backhurst and J. H. Harker, 4th edition (2001), chapter 7, page 318-319, table 7.2.

Appendix 5-6: Gasification

A5-6a: The gasifier

Figure A5-3 shows the downdraft gasifier. In the downdraft gasifier four zones can be distinguished. At the top of the bed the fibres are heated and dried at temperatures from 150°C to 200°C. Below this drying zone the temperatures start to be higher and the fibres release their volatile matter (devolatilization, or pyrolysis). This zone is pyrolysis zone, and the temperature is 400-650 °C. The third zone is combustion zone. In this zone the gaseous products from devolatilization are partially burnt with the existing air. This phenomena is called flaming pyrolysis and it is the source of heat for the drying and pyrolysis as well as for the subsequent char gasification. The temperature in this zone can reach 700-1000°C. In the fourth zone, the char reduction zone, the hot gases formed in the flaming pyrolysis zone (mainly CO2, H2O) react with the remaining char in absence of oxygen at around 700 -900 °C. The char is converted into the product gas mainly by the following endothermic reactions:

Boudouard reaction: $C + CO_2 \leftrightarrow 2CO \qquad \Delta H_R = +160,9 kJ/mol$ eq. A5-6

Water gas reaction: $C + H_2O \leftrightarrow H_2 + CO \qquad \Delta H_R = +118,4 kJ/mol$ eq. A5-7 [1]

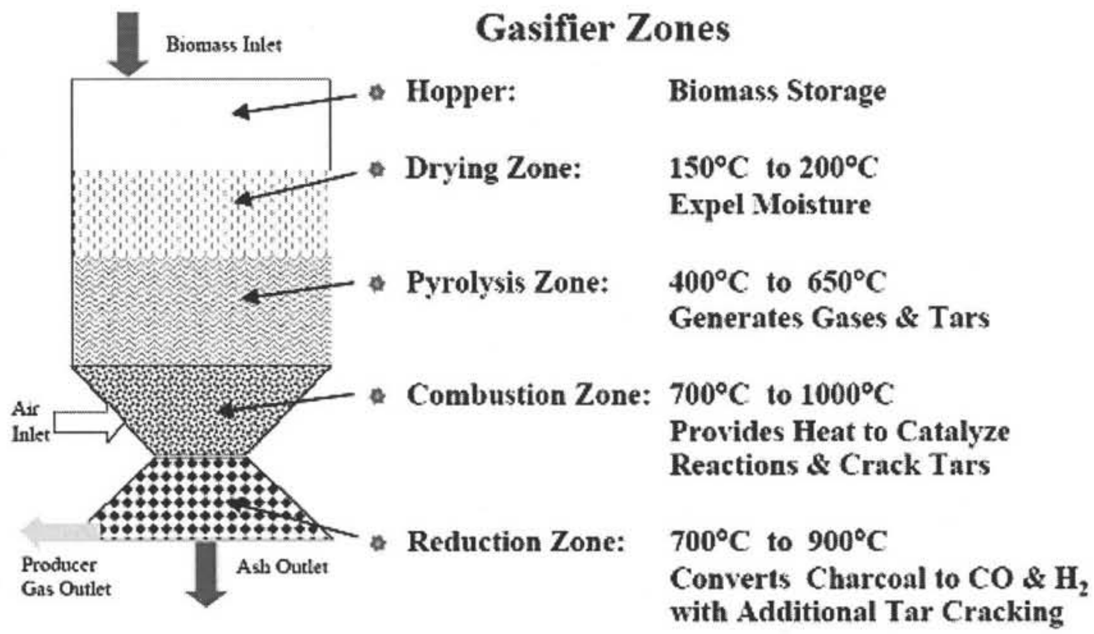


Figure A5-3: Downdraft gasifier [7]

The gas formed in gasification typically consists of ~20% CO, ~20% H_2, ~12% CO_2, 2-3% CH_4. The remaining ~45% consists of nitrogen gas. The gas has a relatively low LHV (5-7 MJ/Nm^3), and has a comparatively high dust content, and acknowledgeable amounts of SO_x and NO_x.

A5-6b: Gas cleaning

The producer gas can contain amongst others corrosive compounds, NO_x, tars and chars, which can be harmful to the engine. Particles in the gas are for a major part in the range of 0.2 to 0.5 µm. A series of steps is commonly used to obtain an acceptable degree of cleansing. The gas is first run through a filter, centrifuge and/or baghouse to remove particles, and later run through a series of scrubbers with the objective of removing corrosives.

The flow rate of gas into the storage tank is quite small (~ 650 Nm^3/h). The gas itself needs to be cleaned to a particulate level below 50 mg/m^3. Due to the small particle size, inertial separation methods are inefficient. However, large unreacted pieces need to be recovered for possible recycle, which can be done using a simple cyclone. For the fines separation, a baghouse is chosen. To obtain good particle capture (95+% [2]), gas velocity through the bags is set at 0.02 m/s, resulting in a required surface area of 8.9 m^2.

The baghouse filter does not reduce the estimated fine particle content (10 g/Nm^3 [3]) below it's legal boundary of 0.02 g/Nm^3. Final purity is obtained by running the filtered gas through a higher efficiency (99%), but low capacity, cartridge filter. The cartridge filter also acts as a policing filter: should anything happen to the baghouse, the cartridge filter can be used while repairing the baghouse.

The exhaust of the engine needs to be cleaned as well, to remove NO_x in compliance with emissions regulations. For this a standard three-way catalyst will be used.

A5-6c: Gas engines

The major engine modifications for a diesel engine include reduction of the compression ratio and installation of an ignition system. The ignition system can either be a spark plug system or a system using diesel fuel in a prechamber as an ignition source for the gas. Direct injection diesel engines are more suited for producer conversion than prechamber engines due to the less heat loss to the cylinder walls, which affect the ignition of the lean producer gas.

Diesel engines fuelled on producer gas are normally operated at a self-aspirated mode. Contaminants in the producer gas, especially particles, can cause damages to a turbocharger. The producer gas is mixed with the intake combustion air and distributed to each cylinder by the intake manifold. For small scale integrated gasification and gas engine system the suction from the gas engine is used to feed air into the gasifier [4].

References:

[1] Modernized biomass energy in China: Jilin, Pat DeLaquil
http://www.nrel.gov/china/pdfs/re_forum/modernized_biomass_energy_in_china.pdf

[2] Low Temperature Particle Filtration of Wood Gas with Low Tar Content
C. Hindsgaul, U. Henriksen and J. D. Bentzen. Proceedings of 12th European Conference and Technology Exhibition on Biomass for Energy, Industry and Climate Protection. Amsterdam June 2002, pp. 494-497.

[3] http://www.giec.ac.cn/chinese/division/cleanfuel/cleantbg/E_gc_1mw.htm

[4] A small-scale stratified downdraft gasifier coupled to a gas engine for combined heat and power production□M. Barrio, M. Fossum#, J.E. Hustad□Norwegian University of Science and Technology
http://www.tev.ntnu.no/MariaBarrio/publikasjoner/article%20gasifier.pdf

Appendix 5-7: Heat Exchangers

All heat exchangers are to be operated in counter-current mode. These are modelled as shown in figure A5-4.

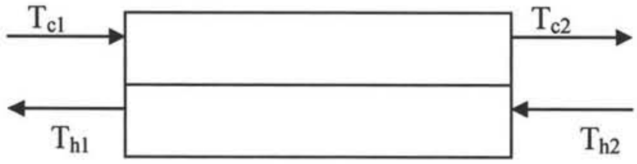


Figure A5-4: Heat exchanger model

Heat is transferred from the hot stream (cooling it from Th2 to Th1), to the cold stream (heating it from Tc1 to Tc2). The heat transferred to the cold stream (Q_c) and the heat transferred from the hot stream are given by:

$$Q_c = F_c \cdot C_{P,c} \cdot \Delta T_c \text{ and} \qquad \text{eq. A5-8}$$

$$Q_h = F_h \cdot C_{P,h} \cdot \Delta T_h \,. \qquad \text{eq. A5-9}$$

Because of conservation of heat, these Q's need to be equal, so defining one gives the other. Once Q is known, the surface area of the heat exchanger can be calculated by:

$$Q = U \cdot A \cdot \Delta T_{\ln}, \text{ where} \qquad \text{eq. A5-10}$$

$$\Delta T_{\ln} = \frac{(T_{h2} - T_{c2}) - (T_{h1} - T_{c1})}{\ln\left(\dfrac{T_{h2} - T_{c2}}{T_{h1} - T_{c1}}\right)} \qquad \text{eq. A5-11}$$

E03 Preheating gasifier air.

Heat exchanger E03 is used to cool the producer gas leaving the gasifier (stream 313) by preheating the air required in gasification (stream 306). In this case, Q is known (heat required to heat air (C_P = 1kJ/kg, F = 2.24·10^{3}ton/a (0.144kg/s) from T_{c1} = 25°C to T_{c2} = 656°C) to be 91.9kW (eq. A5-8).

This cools the producer gas (C_P = 3.51kJ/kg (based on composition), F = 3.81·10^{3}ton/a (0.245kg/s) from T_{h2} = 661°C to T_{h1} = 554°C (eq. A5-9). With all four temperatures know, ΔT_{ln} can be calculated using eq. A5-10 (ΔT_{ln} = 112.4°C). Surface area of the heat exchanger can be determined using eq. A5-11, when a suitable heat transfer coefficient U is known.

For gas-gas heat exchangers, table 12.1 in Coulson & Richardson 6 [1], also used for the other estimates of U) gives a U of 10-50W/m^2 °C. U was assumed to be 25W/m^2 °C, resulting in a heat exchange area of 32.7m^2.

A tube and shell heat exchanger will be used. Due to the high temperature, and the varying composition of the producer gas, corrosion is assumed to be a realistic threat. This leads to the choice of using stainless steel for both tube and shell.

Cost estimate heat exchanger

Investment cost into heat exchangers is done using figure 6.3b from Coulson and Richardson 6. For a completely stainless steel, floating head, and low-pressure heat exchanger with A = 32.7m^2 the cost is read to be: 32 x 1.0 x 1.0 = 32k€.

E02 Cooling condensate evaporator

Stream nr 410, $3.09 \cdot 10^4$ton/a (1.99kg/s), 50°C, needs to be cooled down to 35°C for environmental reasons, using cooling water available at 25°C. Calculations Q are done in a similar way to E03. Q is first determined using the data of the hot stream, and equals 124.5kW. For this Q, F_c is determined to be $4.63 \cdot 10^4$ton/a (2.97kg/s), using eq A5-8, T_{c1} = 25°C and T_{c2} = 35°C. U for water/water transfer, according to C&R, lies in the range 800-1500W/m^2 °C. For this exchanger, U = 1kW/m^2 °C is used to calculate A, which is used to find the base cost in C&R. Due to low temperatures and the use of water only, carbon steel tubes and shell will suffice. For a CS/CS, floating head, low-pressure heat exchanger with A = 10.1m^2, the cost is read to be: 6.2 x 1.0 x 1.0 = 6.2k€.

References:

[1] *J. M Coulson& J F Richardson*, Chemical Engineering, Vol.6, 2001

Appendix 5-8: Pump calculations

A5-8a: Design of Pump P01 (sieved liquid):

1. Speed of pump:

According to the centrifugal pump selection guide [1],

Assume the density of mixture liquid after the disc refiner is 800 [kg/m^3]<

the flow rate of stream after the disc refiner is 14.4 [m^3/hr],

According to the Figure of selection guide [1],

at the point about 14.4 [m^3/hr], the total head is about 40 [m] of water,

and select the Single-stage pump with speed of 3500 [rpm]

$$\text{Specific speed } N_s = \frac{(rmp)*(gpm)^{0.5}}{(head \text{ in ft})^{0.75}} = \frac{3500*(63.4)^{0.5}}{(131.23)^{0.75}} = \frac{27868.44}{38.77} = 718.81$$

Since the maximum head is 500[ft] (152.4 meter) for the single stage of

15-5000 [gpm] centrifugal pumps, this pump designed above is obviously safe [2].

2. Impeller

Pump specific speeds depending on the type of impeller. 400<N_s<1000, the impeller is radial. And the size of the impeller is about 150[mm]. [3].

3. Efficiency

The efficiency of pump is descripting in the Figure 5.9 and Figure10.62 of the book, Chemical Engineering, volume 6. [4] According to the flow rate of stream No.104 that is about 3.32e+4[ton/year]=14.4 [m^3/hr] (when the liquid mixture's density is 800[kg/m^3]), the efficiency of centrifugal pumps is between 45% and 75%, and the head is 40[m], so, the efficiency of pump P01 is about 46% (assumed).

4. Power

$$\text{Power for pumping liquids}=\frac{\text{(gpm)*(psi difference)}}{\text{1714*(fractional efficiency)}} \text{ [2]}$$

Since 1 water column[cm]=0.0142[psi], and 1 [atm]=14.7[psi]

then 40[m]=4000[cm]water column=0.0142*4000=56.8[psi]

Where 1[psi]=6894.76[N/m^2], 1[gallon]=0.0038[m^3], 1[Nm/min]=1.67e-5[kW]

$$\text{so the power}=\frac{63.4*(56.8-14.7)}{1714*46\%} = 3.39[\text{gallon*psi/min}] = 1.48e-3[\text{kW}]$$

The total power consumption in one year is: 1.48e-3*180*16=4.26[kWh]

A5-8b: Design of pump P02 (washing water)

1. Speed of pump:

According to the centrifugal pump selection guide [1],

The density of water is 1000 [kg/m^3]

the flow rate of stream 401 is 4.34 [m^3/hr],

According to the Figure of selection guide [5],

at the point about 4.34 [m^3/hr], the total head is also about 32 [m] of water,

and select the Single-stage pump with speed of 3500 [rpm]

Specific speed $N_s = \frac{(rmp)*(gpm)^{0.5}}{(head \text{ in ft})^{0.75}} = \frac{3500*(19.1)^{0.5}}{(104.99)^{0.75}} = \frac{15296.24}{32.80} = 466.35$

Since the maximum head is 500[ft] (152.4 meter) for the single stage of

15-5000 [gpm] (3.4-1135.59[m^3/hr]) centrifugal pumps,

this pump designed above is obviously safe.[2]

2. Impeller

Pump specific speeds depending on the type of impeller. 400< N_s <1000, the impeller is radial. And the size of the impeller is about 150[mm]. [3].

3. Efficiency

The efficiency of pump is descript in the Figure 5.9 and Figure10.62 of the book, Chemical Engineering, volume 6. [4] According to the flow rate of stream No.401 that is about 1.25e+4[ton/year]= 4.34 [m^3/hr](when water density is 1000[kg/m^3]), the efficiency of centrifugal pumps is between 45% and 75%, and the head is 32[m], so, the efficiency of pump P02 is also about 46%.

4. Power

Power for pumping liquids= $\frac{\text{(gpm)*(psi difference)}}{\text{1714*(fractional efficiency)}}$ [2]

Since 1 water column[cm]=0.0142[psi], and 1 [atm]=14.7[psi]

then 32[m]=3200[cm]water column=0.0142*3200=45.44[psi]

Where 1[psi]=6894.76[N/m^2], 1[gallon]=0.0038[m^3], 1[Nm/min]=1.67e-5[kW]

so the power= $\frac{19.1*(45.44-14.7)}{1714*46\%} = 7.54e-1[\text{gallon*psi/min}] = 3.26e-4[\text{kW}]$

The total power consumption in one year is: 3.26e-4*180*16=0.9389[kWh]

A5-8c: Design of pump P03 (washing water to the refiner)

1. Speed of pump:

According to the centrifugal pump selection guide [5],

The density of water is 1000 [kg/m^3]

the flow rate of stream 405 is 5.63 [m^3/hr],

According to the Figure of selection guide [5],

at the point about 5.63 [m^3 / hr], the total head is also about 32 [m] of water,

and select the Single-stage pump with speed of 3500 [rpm]

Specific speed $N_s = \frac{(rmp)*(gpm)^{0.5}}{(head \text{ in ft})^{0.75}} = \frac{3500*(24.8)^{0.5}}{(104.99)^{0.75}} = \frac{15296.24}{32.80} = 531.40$

Since the maximum head is 500[ft] (152.4 meter) for the single stage of

15-5000 [gpm] (3.4-1135.59[m^3 / hr]) centrifugal pumps,

this pump designed above is obviously safe.[2]

2. Impeller

Pump specific speeds depending on the type of impeller. 400< N_s <1000, the impeller is radial. And the size of the impeller is about 150[mm]. [3].

3. Efficiency

The efficiency of pump is descript in the Figure 5.9 and Figure10.62 of the book, Chemical Engineering, volume 6. [4] According to the flow rate of stream No.401 that is about 1.62e+4[ton/year]= 5.63 [m^3/hr] (when water density is 1000[kg/m^3]), the efficiency of centrifugal pumps is between 45% and 75%, and the head is 32[m], so, the efficiency of pump P03 is also about 46%.

4. Power

Power for pumping liquids= $\frac{\text{(gpm)*(psi difference)}}{\text{1714*(fractional efficiency)}}$ [2]

Since 1 water column[cm]=0.0142[psi], and 1 [atm]=14.7[psi]

then 32[m]=3200[cm]water column=0.0142*3200=45.44[psi]

Where 1[psi]=6894.76[N/m^2], 1[gallon]=0.0038[m^3], 1[Nm/min]=1.67e-5[kW]

so the power= $\frac{24.8*(45.44-14.7)}{1714*46\%} = 9.66e-1[\text{gallon*psi/min}] = 4.23e-4[\text{kW}]$

The total power consumption in one year is: 3.26e-4*180*16=1.2182[kWh]

A5-8d: Design of pump P04 (washing water to the filter)

1. Speed of pump:

According to the centrifugal pump selection guide [1],

The density of water is 1000 [kg/m^3]

the flow rate of water to the filter is 2.45 [m^3/hr],

According to the Figure of selection guide [5],

at the point about 2.45 [m^3/hr], the total head is about 32 [m] of water,

and select the Single-stage pump with speed of 3500 [rpm]

$$\text{Specific speed } N_s = \frac{(rmp)*(gpm)^{0.5}}{(head \text{ in ft})^{0.75}} = \frac{3500*(10.8)^{0.5}}{(104.99)^{0.75}} = \frac{11502.17}{32.80} = 350.68$$

Since the maximum head is 500[ft] (152.4 meter) for the single stage of 15-5000 [gpm] centrifugal pumps, this pump designed above is obviously safe.[2]

2. Impeller

Pump specific speeds depending on the type of impeller. 400<N_s<1000, the impeller is radial. And the size of the impeller is about 150[mm] [3].

3. Efficiency

The efficiency of pump is descripting in the Figure 5.9 and Figure10.62 of the book, Chemical Engineering, volume 6. [4] According to the flow rate of stream No.407 that is about 4.06e+3[ton/year]=2.45 [m^3/hr], the head is 32[m], the efficiency of pump P04 is about 46%.

4. Power

$$\text{Power for pumping liquids} = \frac{\text{(gpm)*(psi difference)}}{\text{1714*(fractional efficiency)}} \quad [2]$$

Since 1 water column[cm]=0.0142[psi], and 1 [atm]=14.7[psi]

then 32[m]=3200[cm]water column=0.0142*3200=45.44[psi]

Where 1[psi]=6894.76[N/m^2], 1[gallon]=0.0038[m^3], 1[Nm/min]=1.67e-5[kW]

$$\text{so the power} = \frac{10.8*(45.44-14.7)}{1714*46\%} = 0.421[\text{gallon*psi/min}] = 1.84e-4[\text{kW}]$$

The total power consumption in one year is: 1.84e-4*180*16=0.5299[kWh]

A5-8e: Design of pump P05 (pump for the waste water)

1. Speed of pump:

According to the centrifugal pump selection guide [5],

The density of water is 1000 [kg/m^3],the water flow rate of stream No.403 is 4.06 [m^3/hr],

According to the Figure of selection guide [1],

at the point about 4.06 [m^3/hr], the total head is about 32 [m] of water,

and select the Single-stage pump with speed of 3500 [rpm]

$$\text{Specific speed } N_s = \frac{(rmp)*(gpm)^{0.5}}{(head \text{ in ft})^{0.75}} = \frac{3500*(17.9)^{0.5}}{(104.99)^{0.75}} = \frac{14807.94}{32.80} = 451.46$$

Since the maximum head is 500[ft] (152.4 meter) for the single stage of 15-5000 [gpm] centrifugal pumps, this pump designed above is safe.[2]

2. Impeller

Pump specific speeds depending on the type of impeller. 400< N_s <1000, the impeller is radial. And the size of the impeller is about 150[mm]. [3].

3. Efficiency

The efficiency of pump is descripting in the Figure 5.9 and Figure10.62 of the book, Chemical Engineering, volume 6. [4] According to the flow rate of stream No.403 that is 1.17e+4[ton/year]= 4.06 [m^3/hr], and the head is 32[m], so the efficiency of centrifugal pump is about 46%.

4. Power

$$\text{Power for pumping liquids}=\frac{\text{(gpm)*(psi difference)}}{\text{1714*(fractional efficiency)}} \quad [2]$$

Since 1 water column[cm]=0.0142[psi], and 1 [atm]=14.7[psi]

then 32[m]=3200[cm]water column=0.0142*3200=45.44[psi]

Where 1[psi]=6894.76[N/m^2], 1[gallon]=0.0038[m^3], 1[Nm/min]=1.67e-5[kW]

$$\text{so the power}=\frac{17.9*(45.44-14.7)}{1714*46\%}=0.697[\text{gallon*psi/min}]=3.05e-4[\text{kW}]$$

The total power consumption in one year is: 3.05e-4*180*16=0.8784[kWh]

A5-8f: Design of pump P06 (liquid mixture with fiber)

1. Speed of pump:

According to the centrifugal pump selection guide [1],

The density of mixture is 970 [kg/m^3],the flow rate of stream No.201 is 12.7 [m^3/hr],7

According to the Figure of selection guide [1],

at the point about 12.7 [m^3/hr], the total head is about 32 [m] of water,

and select the Single-stage pump with speed of 3500 [rpm]

$$\text{Specific speed } N_s=\frac{(rmp)*(gpm)^{0.5}}{(head \text{ in ft})^{0.75}}=\frac{3500*(55.9)^{0.5}}{(104.99)^{0.75}}=\frac{26168.21}{32.8}=797.81$$

Since the maximum head is 500[ft] (152.4 meter) for the single stage of 15-5000 [gpm] centrifugal pumps, this pump designed above is obviously safe.[2]

2. Impeller

Pump specific speeds depending on the type of impeller. 400< N_s <1000, the impeller is radial. And the size of the impeller is about 150[mm] [3].

3. Efficiency

The efficiency of pump is descripting in the Figure 5.9 and Figure10.62 of the book, Chemical Engineering, volume 6 [4]. According to the flow rate of stream No.201 that is about 3.55e+4[ton/year]=12.7 [m^3/hr], the efficiency of centrifugal pumps is between 45% and 75%, and the head is 32 [m], so, the efficiency of pump P06 is also about 46%.

4. Power

Power for pumping liquids= $\frac{\text{(gpm)*(psi difference)}}{\text{1714*(fractional efficiency)}}$ [2]

Since 1 water column[cm]=0.0142[psi], and 1 [atm]=14.7[psi]

then 32[m]=3200[cm]water column=0.0142*3200=45.44[psi]

Where 1[psi]=6894.76[N/m^2], 1[gallon]=0.0038[m^3], 1[Nm/min]=1.67e-5[kW]

so the power= $\frac{55.9*(45.44-14.7)}{1714*46\%} = 2.18[\text{gallon*psi/min}] = 9.54e-4[\text{kW}]$

The total power consumption in one year is: 9.54e-4*180*16=2.75[kWh]

A5-8g: Design of pump P07 (water out of evaporator)

1. Speed of pump:

According to the centrifugal pump selection guide [5],

The density of water is 1000 [kg/m^3],the flow rate of stream No.409 is 12.5 [m^3/hr],

According to the Figure of selection guide [1],

at the point about 12.2 [m^3 / hr], the total head is about 32 [m] of water,

and select the Single-stage pump with speed of 3500 [rpm]

Specific speed $N_s = \frac{(rmp)*(gpm)^{0.5}}{(head \text{ in ft})^{0.75}} = \frac{3500*(55)^{0.5}}{(104.99)^{0.75}} = \frac{25956.6947}{32.8} = 791.36$

Since the maximum head is 500[ft] (152.4 meter) for the single stage of 15-5000 [gpm] centrifugal pumps, this pump designed above is obviously safe.[2]

2. Impeller

Pump specific speeds depending on the type of impeller. 400< N_s <1000, the impeller is radial. And the size of the impeller is about 150[mm] [3].

3. Efficiency

The efficiency of pump is descripting in the Figure 5.9 and Figure10.62 of the book, Chemical Engineering, volume 6. [4] According to the flow rate of stream No.409 that is about 3.60e+4[ton/year]=12.5[m^3/hr], the efficiency of centrifugal pumps is between 45% and 75%, and the head is 32 [m], so, the efficiency of pump P07 is also about 46%.

4. Power

Power for pumping liquids= $\frac{\text{(gpm)*(psi difference)}}{\text{1714*(fractional efficiency)}}$ [2]

Since 1 water column[cm]=0.0142[psi], and 1 [atm]=14.7[psi]

then 32[m]=3200[cm]water column=0.0142*3200=45.44[psi]

Where 1[psi]=6894.76[N/m^2], 1[gallon]=0.0038[m^3], 1[Nm/min]=1.67e-5[kW]

so the power= $\frac{55*(45.44-14.7)}{1714*46\%} = 2.15[\text{gallon*psi/min}] = 9.39e-4[\text{kW}]$

The total power consumption in one year is: 9.39e-4*180*16=2.70[kWh]

A5-8h: Design of pump P08 (concentrated sugar liquid)

1. Speed of pump:

According to the centrifugal pump selection guide [5],

The density of concentrated sugar liquid is 1100 [kg/m^3],

the flow rate of stream No.203 is 1.24 [m^3/hr],

According to the Figure of selection guide [1],

at the point about 1.24 [m^3 / hr], the total head is about 32 [m] of water,

and select the Single-stage pump with speed of 3500 [rpm]

Specific speed $N_s = \frac{(rmp)*(gpm)^{0.5}}{(head \text{ in ft})^{0.75}} = \frac{3500*(5.46)^{0.5}}{(104.99)^{0.75}} = \frac{8178.33}{32.8} = 249.34$

Since the maximum head is 500[ft] (152.4 meter) for the single stage of 15-5000 [gpm] centrifugal pumps, this pump designed above is obviously safe.[2]

2. Impeller

Pump specific speeds depending on the type of impeller. 400< N_s <1000, the impeller is radial. And the size of the impeller is about 150[mm] [3].

3. Efficiency

The efficiency of pump is descripting in the Figure 5.9 and Figure10.62 of the book, Chemical Engineering, volume 6 [4]. According to the flow rate of stream No.203 that is about 3.94e+3[ton/year]=1.24[m^3/hr], the efficiency of centrifugal pumps is between 45% and 75%, and the head is 32 [m], so, the efficiency of pump P08 is also about 46%.

4. Power

Power for pumping liquids= $\frac{\text{(gpm)*(psi difference)}}{\text{1714*(fractional efficiency)}}$ [2]

Since 1 water column[cm]=0.0142[psi], and 1 [atm]=14.7[psi]

then 32[m]=3200[cm]water column=0.0142*3200=45.44[psi]

Where 1[psi]=6894.76[N/m^2], 1[gallon]=0.0038[m^3], 1[Nm/min]=1.67e-5[kW]

so the power= $\frac{5.46*(45.44-14.7)}{1714*46\%} = 0.213[\text{gallon*psi/min}] = 9.31e-5[\text{kW}]$

The total power consumption in one year is: 9.31e-5*180*16=0.268[kWh]

A5-8i: Design of pump P09 (diesel supply)

1. Speed of pump:

According to the centrifugal pump selection guide [5],

The density water is 1000 [kg/m^3],

the flow rate of stream No.415 is 1.55 [m^3/hr],

According to the Figure of selection guide [1],

at the point about 1.55 [m^3 / hr], the total head is about 32 [m] of water,

and select the Single-stage pump with speed of 3500 [rpm]

Specific speed $N_s = \dfrac{(rmp)*(gpm)^{0.5}}{(head \text{ in ft})^{0.75}} = \dfrac{3500*(6.82)^{0.5}}{(104.99)^{0.75}} = \dfrac{9140.30}{32.8} = 278.67$

Since the maximum head is 500[ft] (152.4 meter) for the single stage of 15-5000 [gpm] centrifugal pumps, this pump designed above is obviously safe.[2]

2. Impeller

Pump specific speeds depending on the type of impeller. 400< N_s <1000, the impeller is radial. And the size of the impeller is about 150[mm] [3].

3. Efficiency

The efficiency of pump is descripting in the Figure 5.9 and Figure10.62 of the book, Chemical Engineering, volume 6 [4]. According to the flow rate of stream No.415 that is about 4.46e+3[ton/year]=1.55[m^3/hr], the efficiency of centrifugal pumps is between 45% and 75%, and the head is 32 [m], so, the efficiency of pump P09 is also about 46%.

4. Power

Power for pumping liquids=$\dfrac{\text{(gpm)*(psi difference)}}{\text{1714*(fractional efficiency)}}$ [2]

Since 1 water column[cm]=0.0142[psi], and 1 [atm]=14.7[psi]

then 32[m]=3200[cm]water column=0.0142*3200=45.44[psi]

Where 1[psi]=6894.76[N/m^2], 1[gallon]=0.0038[m^3], 1[Nm/min]=1.67e-5[kW]

so the power=$\dfrac{6.82*(45.44-14.7)}{1714*46\%} = 0.266[\text{gallon*psi/min}] = 1.16e-4[\text{kW}]$

The total power consumption in one year is: 1.16e-4*180*16=0.334[kWh]

A5-8j: Design of Blower and Fans:

Power(kw)=$2.72*10^{-5}*Q*P$, where Q is the fan volume (m^3 / hour) and P is the total discharge pressure in cm of water column.

First, taking P_1 and P_2 as the pressures at the upsteam and downstream ends of the pipe.

Then, $\Delta P = P_1 - P_2 = 4*\phi*\frac{l}{d}*\rho*u^2$,

and $\phi*\mathrm{Re}^2 = \frac{R}{\rho*u^2}*(\frac{\rho*u*d}{\mu})^2 = \frac{\Delta P*d^3*\rho}{4*l*\mu^2}$

where u is the viscosity of gas, about $9*10^{-6}[Ns/m^2]$

According to the figure of $\phi*\mathrm{Re}^2$ versus Re [8], assume e/d(roughness)=0.001

the velocity of air is $u = \frac{272[m^3/hr]}{\pi*d^2*\frac{1}{4}[m^2]} = 3850[m/hr] = 1.07[m/s]$

then, for air (298K):

$$\mathrm{Re} = \frac{\rho*u*d}{\mu} = \frac{1.29[kg/m^3]*1.07[m/s]*0.3[m]}{9*10^{-6}[Ns/m^2]} = 4.601*10^4$$

the value of $\phi*\mathrm{Re}^2 = 6*10^6 = \frac{\Delta P*d^3*\rho}{4*l*\mu^2}$,

$$\text{then,}\Delta P = \frac{6*10^6*4*10[m]*(9*10^{-6}[Ns/m^2])^2}{0.3^3[m^3]*1.29[kg/m^3]} = 5.58[N/m^2] = 5.58*10^{-5}[bar]$$

For Gas (1033K)

The flow rate of gas is 1340[m^3/hour]=0.372[m^3/s]

The velocity of gas is $u = \frac{0.372[m^3/s]}{\pi*d^2*\frac{1}{4}[m^2]} = 5.26[m/s]$

$$\mathrm{Re} = \frac{\rho*u*d}{\mu} = \frac{1[kg/m^3]*5.26[m/s]*0.3[m]}{9*10^{-6}[Ns/m^2]} = 1.75*10^5$$

the value of $\phi*\mathrm{Re}^2 = 5*10^7 = \frac{\Delta P*d^3*\rho}{4*l*\mu^2}$,

$$\text{then,}\Delta P = \frac{5*10^7*4*4[m]*(9*10^{-6}[Ns/m^2])^2}{0.3^3[m^3]*1[kg/m^3]} = 24[N/m^2] = 2.4*10^{-4}[bar]$$

For Gas (313K)

The flow rate of gas is 1450[m^3/hour]=0.4028[m^3/s]

The velocity of gas is $u=\dfrac{0.4028[m^3/s]}{\pi*d^2*\frac{1}{4}[m^2]}=5.70[m/s]$

$$Re=\frac{\rho*u*d}{\mu}=\frac{1[kg/m^3]*5.70[m/s]*0.3[m]}{9*10^{-6}[Ns/m^2]}=1.90*10^5$$

the value of $\phi*Re^2=5.5*10^7=\dfrac{\Delta P*d^3*\rho}{4*l*\mu^2}$,

then, $\Delta P=\dfrac{5.5*10^7*4*4[m]*(9*10^{-6}[Ns/m^2])^2}{0.3^3[m^3]*1[kg/m^3]}=26.4[N/m^2]=2.64*10^{-4}[bar]$

For Steam (323K)

The flow rate of gas is 6050[m^3/hour]=1.68[m^3/s]

The velocity of gas is $u=\dfrac{1.68[m^3/s]}{\pi*d^2*\frac{1}{4}[m^2]}=23.77[m/s]$

$$Re=\frac{\rho*u*d}{\mu}=\frac{0.0936[kg/m^3]*23.77[m/s]*0.3[m]}{1*10^{-5}[Ns/m^2]}=6674.616$$

he viscosity of steam is $1*10^{-5}[Ns/m^2]$[6]

the value of $\phi*Re^2=2.10*10^5=\dfrac{\Delta P*d^3*\rho}{4*l*\mu^2}$,

then, $\Delta P=\dfrac{2.10*10^5*4*8[m]*(1.0*10^{-5}[Ns/m^2])^2}{0.3^3[m^3]*0.0936[kg/m^3]}=265.91[N/m^2]=2.66*10^{-3}[bar]$

Thus, the power consumptions are:

Table A5-15: Power consumptions

1 bar =	1019.72 (cm water column)
5.58E-05	5.69E-02
2.40E-04	2.45E-01
2.64E-04	2.69E-01
2.66E-03	2.71E+00

Power(kw)=$2.72*10^{-5}*Q*P$

Table A5-16: Blower power consumptions

No.	m3/hr	kW	kWh
K01	2.72E+02	4.21E-04	1.21E+00
K02	1.34E+03	8.92E-03	2.57E+01
K03	1.45E+03	1.06E-02	3.06E+01
K03	6.05E+03	4.46E-01	1.28E+03

References:

[1] Chemical engineering volume 6: Chemical Engineering Design, R K Sinnot, 3rd edition (2000), Chapter 5, page 199, Figure 5.6.

[2] Process Design Principles: Synthesis, analysis, and evaluation. Warren D. Seider, J.D. Seader, Daniel R. Lewin. Appendix X, page 804.

[3] Chemical engineering volume 6: Chemical Engineering Design, R K Sinnot, 3rd edition (2000), Chapter 5, page 208, Figure 5.10.

[4] Chemical engineering volume 6: Chemical Engineering Design, R K Sinnot, 3rd edition (2000), Chapter 5, page 206, Figure 5.9, page 478, Figure 10.62.

[5] Chemical engineering volume 1: Fluid Flow, Heat Transfer and Mass Transfer, J.M.Coulson and J.F.Richardson with J.R. Backhurst and J.H. Harker, 6th edition (1999), Chapter 8, page 336, Figure 8.25.

[6] Chemical engineering volume 1: Fluid Flow, Heat Transfer and Mass Transfer, J.M.Coulson and J.F.Richardson with J.R. Backhurst and J.H. Harker, 6th edition (1999), Appendix 1, page 899.

[7] http://www.univ-reims.fr/Externes/AVH/MementoSugar/001.htm

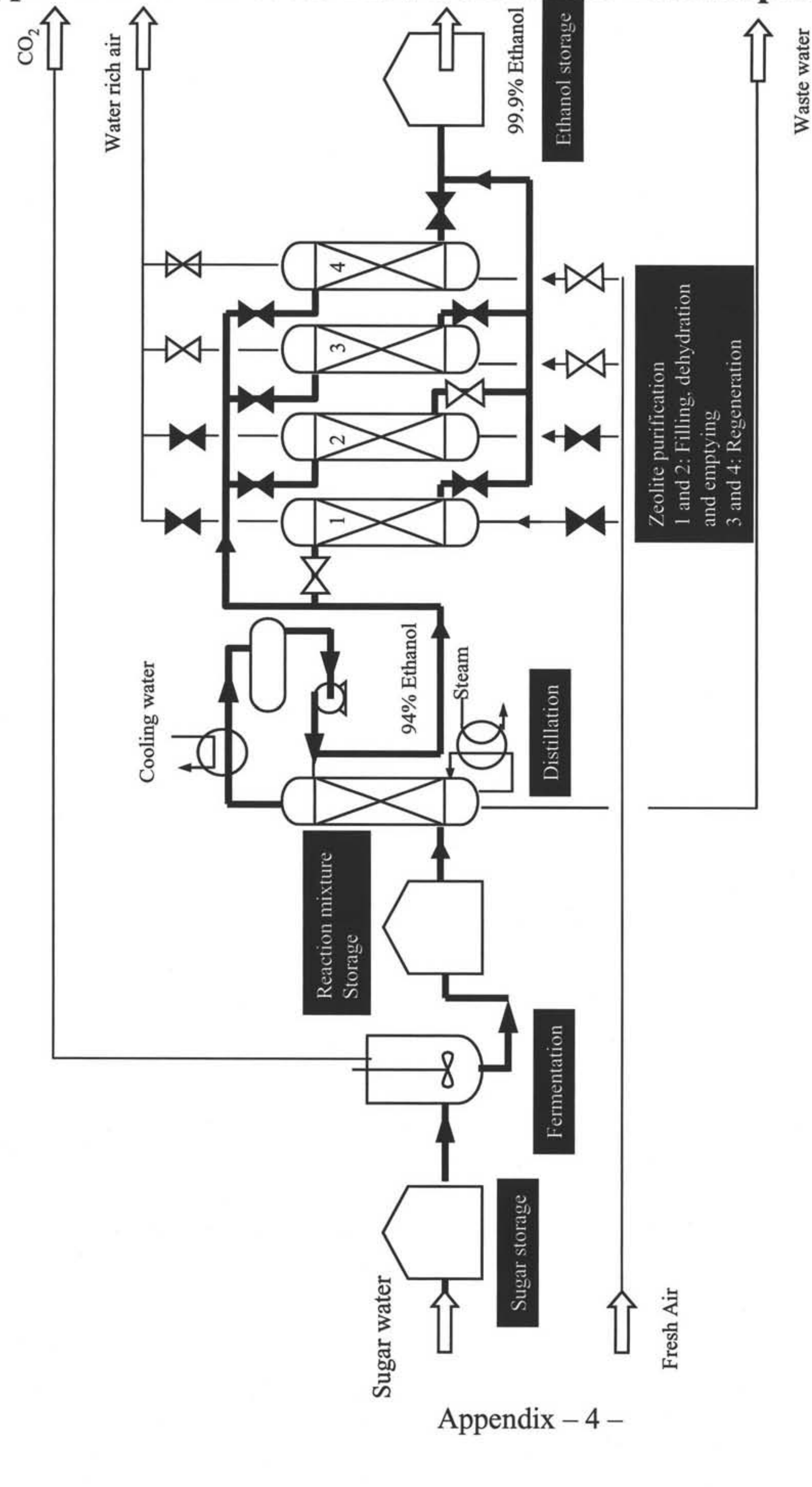
[8] http://www.networkintl.com/attachments/catalog/web_6025_principalparts.pdf

Appendix 5-9: Utility summary

The requirements of utilities (1 year = 180 days)

UTILITY REQUIREMENTS									
				Requirements					
Name	*Function*	Utility type	*Load* (kW)	CW (kg/h)	Steam (kg/h)	*Electricity* (kWh/a)	CW (ton/a)	Steam (ton/a)
E01	Evaporator	Steam	9.04E+02		8.31E+00			3.59E+04
E02	Condenser	CW	1.24E+02	1.07E+01			4.63E+04	
P01	Pump	Electricity	1.48E+03			4.26E+06		
P02	Pump	Electricity	3.26E-04			9.39E-01		
P03	Pump	Electricity	4.23E-04			1.22E+00		
P04	Pump	Electricity	1.84E-04			5.30E-01		
P05	Pump	Electricity	3.05E-04			8.78E-01		
P06	Pump	Electricity	9.54E-04			2.75E+00		
P07	Pump	Electricity	9.39E-04			4.06E+00		
P08	Pump	Electricity	9.31E-05			4.02E-01		
P09	Pump	Electricity	1.16E-04			5.01E-01		
K01	Blower	Electricity	4.21E-04			1.82E+00		
K02	Blower	Electricity	8.92E-03			3.85E+01		
K03	Blower	Electricity	1.06E-02			4.58E+01		
K04	Blower	Electricity	4.46E-01			1.93E+03		
X01	Transport	Electricity	2.20E+00			6.34E+03		
X02	Transport	Electricity	2.20E+00			6.34E+03		
X03	Transport	Electricity	2.20E+00			6.34E+03		
X04	Transport	Electricity	2.20E+00			6.34E+03		
X05	Belt Dryer	Electricity	2.20E+00			9.50E+03		
X06	Belt Dryer	Electricity	2.20E+00			9.50E+03		
X07	Transport	Electricity	2.20E+00			9.50E+03		
A01	Disc Refiner	Electricity	2.24E+02			6.45E+05		
S01	Drum filter	Electricity	5.00E+00			1.44E+04		
V01	Hooper& Chopper	Electricity	9.74E+00			2.81E+04		
Total			**2.76E+03**	**1.07E+01**	**8.31E+00**	**5.01E+06**	**4.63E+04**	**3.59E+04**

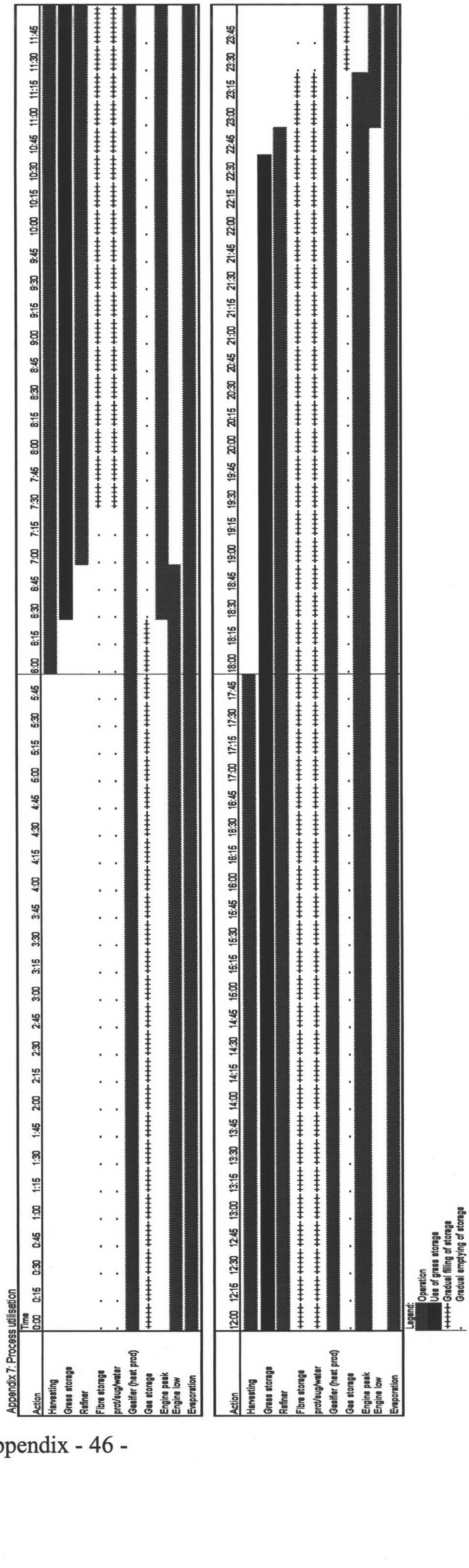
Appendix 6a – Process Flow Scheme for ethanol production



Appendix 6b: Process stream summary of ethanol production

	from 1 farm	from 3 farms									
Name :	conc. sugar/protein	conc. sugar/protein	produced protein	filtrate	make up water	total sugar	yeast growth	fermentor input	fermentor output	yeast cake	input destillation
COMP	ton/a	ton/a									
Water	1370	4110	191	3919	12211	16130	484	15646	15646	782	14864
Yeast (only addition produced)									132	132	
Ash	988	2964	89	2875		2875	86	2789	2777	139	2638
Protein	563	1690	1673	17		17	1	16			
Sugar	1635	4904	147	4757		4757	143	4614	1153	58	1096
Ethanol									1384	69	1315
CO2									1903	95	1808
Acetic acid									35	2	33
Furfural									35	2	33
Total flow	4556	13668	2100	11568	12211	23779	713	23065	23065	1279	21786
Enthalpy kW											
phase L/V/S	L	L	S	L	L	L	L	L	L/S	L/S	L
Press. bara	1	1	1	1	1	1	1	1	1	1	1
Temp °C	50	50	35	35	25	25	35	35	35	35	35

Appendix 7: Process utilisation



Appendix 8-1a: Dow Fire and Explosion Index (FEI) for gasification

Unit: consider the total plant, no separate areas.
Material factor: for producer gas, MF = 21

General process hazards:

A. Exothermic chemical reactions: not applicable
B. Endothermic chemical reactions: The energy source is provided by the combustion of a solid (fibre), factor = 0.4
C. Materials handling and transfer: flammable gases storage, factor = 0.5
D. Enclosed and indoor process units: not applicable
E. Access of emergency equipment: Adequate access would be provided, factor = 0.0
F. Drainage and spill control: Adequate drainage would be provided, factor = 0.0

Special process hazards:

A. Toxic material: CO is present in producer gas. N_h of CO is 3, factor = 0.2*3=0.6
B. Sub-atmospheric pressure: The pressure is 1 bar, not applicable
C. Operation in or near flammable range: Process or operation which could be in or near the flammable range only in case of instrument or equipment upsets or purge failure. Factor = 0.3
D. Dust explosion: not applicable
E. Relief pressure: The pressure is 1 bar, not applicable
F. Low temperature: No any operation is lower than 10°C, not applicable
G. Quantity of flammable material: The largest quantity of producer gas in the process will be in the gas storage tank, which is 13757 lb. The quantity of H_2 is 13757*20.3% = 2793 lb; Heat of combustion for H_2, Hc = 51.6×10^3 BTU/lb
   Potential energy release = 2793lbs*51.6×10^3 BTU/lb= $0.14 * 10^9$ BTU
   Factor = 0.17
H. Corrosion and erosion: Corrosion resistant materials of construction would be specified, but external corrosion is possible, hence allow minimum factor = 0.1
I. Leakage – joints and packing: Welded joints will be used on gasification unit and mechanical seals on pumps. Use minimum factor 0.1 as full equipment details are not known at the flow sheet stage, hence factor = 0.1;
J. Use of fired heaters: A furnace is used in the process, which is heated by combustion of fibre not fuels. Not applicable.
K. Hot oil heat exchange system: Heat exchange system only uses steam as heating medium, not applicable.
L. Rotating equipment: Disc refiner is used in the process, factor = 0.5

DOW FIRE AND EXPLOSION INDEX (FEI)		LOCATION Zambia		DATE 15-Dec-03
PLANT Refine green grass (produce protein cake and electricity)	PROCESS UNIT Whole plant	EVALUATED BY		REVIEWED BY
MATERIALS AND PROCESS				
MATERIALS IN PROCESS UNIT Grass, protein, sugar, fiber, producer gas(CO, H_2, CO_2, CH_4, N_2) oxygen, water				
STATE OF OPERATION [ ] START UP [ ] SHUT DOWN [V] NORMAL OPERATION		Basic Material For MF Producer gas (H_2)		
MATERIAL FACTOR (MF)				21
1. GENERAL PROCESS HAZARD		Penalty Factor Range	Penalty Factor Used	
BASE FACTOR		1.00	1.00	
A. EXOTHERMIC CHEMICAL REACTIONS		0.30 to 1.25		
B. ENDOTHERMIC PROCESSES		0.20 to 0.40	0.40	
C. MATERIAL HANDLING AND TRANSFER		0.25 to 1.05	0.50	
D. ENCLOSED OR INDOOR PROCESS UNITS		0.25 to 0.90		
E. ACCESS		0.25 to 0.35		
F. DRAINAGE AND SPILL CONTROL		0.25 to 0.50		
GENERAL PROCESS HAZARDS FACTOR (F_1)			1.90	
2. SPECIAL PROCESS HAZARDS				
BASE FACTOR		1.00	1.00	
A. TOXIC MATERIALS		0.20 to 0.80	0.60	
B. SUB-ATMOSPHERIC PRESSURE (<500 mm Hg)		0.50		
C. OPERATION IN OR NEAR FLAMMABLE RANGE				
[ ] INERTED [ ] NOT INERTED				
1. TANK FARMS STORAGE FLAMMABLE LIQUIDS		0.50		
2. PROCESS UPSET OR PURGE FAILURE		0.30	0.30	
3. ALWAYS IN FLAMMABLE RANGE		0.80		
D. DUST EXPLOSION		0.25 to 2.00		
E. PRESSURE: OPERATING PRESSURE: 1 bar				
F. LOW TEMPERATURE		0.20 to 0.30		
G. QUANTITY OF FLAMMABLE / UNSTABLE MATERIAL: QUANTITY: 2793 lbs $Hc = 51.6x10^3$ BTU/lb				
1. LIQUIDS, GASES AND REACTIVE MATERIALS IN PROCESS				
2. LIQUIDS OR GASES IN STORAGE			0.17	
3. COMBUSTIBLE SOLIDS IN STORAGE DUST IN PROCESS				
H. CORROSION AND EROSION		0.10 to 0.75	0.10	
I. LEAKAGE-JOINTS AND PACKING		0.10 to 1.50	0.10	
J. USE OF FIRED HEATERS				
K. HOT OIL HEAT EXCHANGE SYSTEM		0.15 to 1.15		
L. ROTATING EQUIPMENT		0.50	0.5	
SPECIAL HAZARD FACTOR (F_2)			2.77	
UNIT HAZARD FACTOR ($F_1 \times F_2 = F_3$)			5.26	
FIRE AND EXPLOSION INDEX (F3 x MF = F&EI)				110

Appendix 8-1b: Hazard and operability study analysis for gasification

Vessel – Gasifier
Intention – Combust fibre with limited air to produce producer gas

Guide Word	Deviation	Possible Causes	Consequences	Action Required
Line number: No. 303 Intention: Transfers dry fibre to gasifier				
No	No Flow	1) No fibre available in storage tank 2) Elevator (X07) fails (no power, motor fault, loss of drive, ect)	Loss of feed to reactor and reduce output As for 1)	a) Ensure good communications with storage tank operator; b) Ensure good communications with elevator operator; c) Install elevator fault alarm
More	More Flow	3) Speed of elevator is high in error	Reactor overfills; Air is not enough for combustion of fibre in oxidation zone	Covered by b) and c)
Less	Less Flow	4) Speed of elevator is low in error	Low rate of production	Covered by b) and c)
Line number: No. 304,305,306,308 Intention: Transfers air to gasifier				
No	No Flow	5) Blower (K01) failure 6) FC valve fails close 7) Line fracture	Air is not enough for combustion of fibre in oxidation zone; Loss of feed to reactor and reduce conversion As for 5) As for 5)	d) Install low flow pressure alarm interlocked to shut down fibre flow. Covered by d) e) Institute regular patrolling and inspection of transfer line
More	More Flow	8) FC valve opens too wide in error	Explosions can occur if the gas is mixed with sufficient air to	f) Check the valves periodically to ensure that it works as expected; Install

			form an explosive mixture; Completely fibre combustion in oxidation zone, no reduction reactions.	emergency valves
	More Temperature	9) Heat exchanger (E03) partial failure	High reactor temperature	g) Check the heat exchanger periodically to ensure that it works as expected
		10) Flow rate of line NO.313 is high	As for 9)	h) Install temperature controller by adjusting the flow rate of line NO.313
Less	Less Flow	11) Blower (K01) partial failure	As for 5)	Covered by d)
		12) FC valve close too much in error	As for 5)	Covered by d) and f)
	Less temperature	13) Heat exchanger (E03) partial failure	Low reactor temperature	Covered by g)
		14) Flow rate of line NO.313 is low	As for 14)	Covered by h)
Reverse	Reverse Flow	15) High pressure at gasifier	Producer gas leaks into air, explosion and toxic hazard	i) Fit non-return valve
Line number: No. 311,313,314,315,316 Intention: Transfers producer gas out of gasifier to baghouse (S02)				
No	No Flow	16) Blower (K02) fails (motor fault, loss of drive, etc)	Explosion could occur because the pressure of gasifier (R01) increases and producer gas	j) Install high pressure alarm on gasifier interlocked to shut down firbre flow.

			mixes with air	
		17) Line blockage	As for 16)	Covered by j)
		18) TC valve of E03 closes in error	As for 16)	Covered by f) and j)
		18) Line fracture	Toxic producer gas leaks into air	Covered by e)
Less	Less Flow	19) Blower (K02) partial failure	As for 16)	Covered by j)
		20) TC valve of E03 closes too much in error	As for 16)	Covered by f) and j)
Reverse	Reverse Flow	21) Low pressure at gasifier	Explosions can occur if the gas is mixed with sufficient air to form an explosive mixture;	Fit non-return valve

Appendix 8-2a: Dow Fire and Explosion Index for ethanol production

General process hazards:

A. Exothermic reactions: fermentation is not mentioned, but it is, in relation to the chemical processes mentioned, a mild process, so the lowest penalty was chosen: 0.30.

B. Endothermic reactions: do not happen here so penalty = 0.

C. Materials handling and transfer: storage of ethanol, a flammable liquid, so penalty = 0.85.

D. Enclosed process units: all units will be in the open, so penalty = 0.

E. Access: Land is not expensive in Zambia, so all units will be placed so that access is good. So the penalty = 0.

F. Drainage: Since the plant can be completely designed as safe as possible, spill will be directed away to an impounding basis, which results in a penalty = 0.25.

Special process hazards:

A. Process temperature: In the distillation column ethanol vapor is present, so temperature above the boiling points are present, which result in penalty = 0.60.

B. Low pressure: no sub-atmospheric pressure, so penalty = 0.

C. Operation in or near flammable region: ethanol is stored, and the possibility of air intake exists, so the penalty = 0.5.

D. Dust explosion: no dust present, so penalty = 0.

E. Relief pressure: all operations are at atmospheric pressure, so penalty = 0.

F. Low temperature: the lowest temperature in the process in 25 degrees, so penalty = 0.

G. Quantity of Flammable Material: the most ethanol will be present in the storage tank. The most possible present is 20 ton. This corresponds to 44 093 lbm. Together with the $11.5 \cdot 10^3$ BTU per pound this results in 0.5×10^9 BTU. Ethanol is a Class I flammable liquid, so the penalty = 0.30.

H. Corrosion and erosion: water as well as organic acids are present in the fermentor and distillation, so proper corrosion prevention materials must be used, still the possibility of corrosion can not be ruled out, so a penalty of 0.20.

I. Leakage: The 4 dehydration vessels have valves that open and close several times a day. This gives an increased chance of leakage, which result in a penalty = 0.30.

J. Use of fired heaters: the bottom of the distillation column will be heated by steam created in a direct fired heater, which burn fibres or ethanol, since land is not expensive the heater will be placed far enough away from the process units, but no more than 40 meters. This results in a penalty of 0.18.

K. Hot oil exchange systems: no such units present, so penalty = 0.

L. Rotating equipment: the stirrer in the fermentor is needed for adequate heat transfer, if it breaks down, an exothermic reaction (runaway) can ocure, so a penalty = 0.50.

DOW FIRE AND EXPLOSION INDEX (FEI)		LOCATION Zambia		DATE 08-Dec-03
PLANT Ethanol producing and purification plant	PROCESS UNIT Whole plant	EVALUATED BY J.M. Suijker		REVIEWED BY T.V. Pfeiffer
MATERIALS AND PROCESS				
MATERIALS IN PROCESS UNIT Water, CO_2, ethanol as major components. Also: air, acetic acid, furfural, and all kinds of biological components				
STATE OF OPERATION [ ] START UP [ ] SHUT DOWN [V] NORMAL OPERATION		Basic Material For MF Ethanol		
MATERIAL FACTOR (MF)				16
1. GENERAL PROCESS HAZARD		Penalty Factor Range	Penalty Factor Used	
BASE FACTOR		1.00	1.00	
A. EXOTHERMIC CHEMICAL REACTIONS		0.30 to 1.25	0.30	
B. ENDOTHERMIC PROCESSES		0.20 to 0.40		
C. MATERIAL HANDLING AND TRANSFER		0.25 to 1.05	0.85	
D. ENCLOSED OR INDOOR PROCESS UNITS		0.25 to 0.90		
E. ACCESS		0.25 to 0.35		
F. DRAINAGE AND SPILL CONTROL		0.25 to 0.50		
GENERAL PROCESS HAZARDS FACTOR (F_1)			2.15	
2. SPECIAL PROCESS HAZARDS				
BASE FACTOR		1.00	1.00	
A. Process Temperature		0.20 to 0.80	0.60	
B. SUB-ATMOSPHERIC PRESSURE (<500 mm Hg)		0.50		
C. OPERATION IN OR NEAR FLAMMABLE RANGE				
[ ] INERTED [V] NOT INERTED				
1. TANK FARMS STORAGE FLAMMABLE LIQUIDS		0.50	0.50	
2. PROCESS UPSET OR PURGE FAILURE		0.30		
3. ALWAYS IN FLAMMABLE RANGE		0.80		
D. DUST EXPLOSION		0.25 to 2.00		
E. PRESSURE: OPERATING PRESSURE: 1 bar				
F. LOW TEMPERATURE		0.20 to 0.30		
G. QUANTITY OF FLAMMABLE / UNSTABLE MATERIAL:				
QUANTITY: 44,000 lbs Hc = 11.5×10^3 BTU/lb				
1. LIQUIDS, GASES AND REACTIVE MATERIALS IN PROCESS				
2. LIQUIDS OR GASES IN STORAGE			0.30	
3. COMBUSTIBLE SOLIDS IN STORAGE DUST IN PROCESS				
H. CORROSION AND EROSION		0.10 to 0.75	0.20	
I. LEAKAGE-JOINTS AND PACKING		0.10 to 1.50	0.30	
J. USE OF FIRED HEATERS			0.18	
K. HOT OIL HEAT EXCHANGE SYSTEM		0.15 to 1.15		
L. ROTATING EQUIPMENT		0.50	0.50	
SPECIAL HAZARD FACTOR (F_2)			3.58	
UNIT HAZARD FACTOR ($F_1 \times F_2 = F_3$)			7.70	
FIRE AND EXPLOSION INDEX (F3 x MF = F&EI)				123

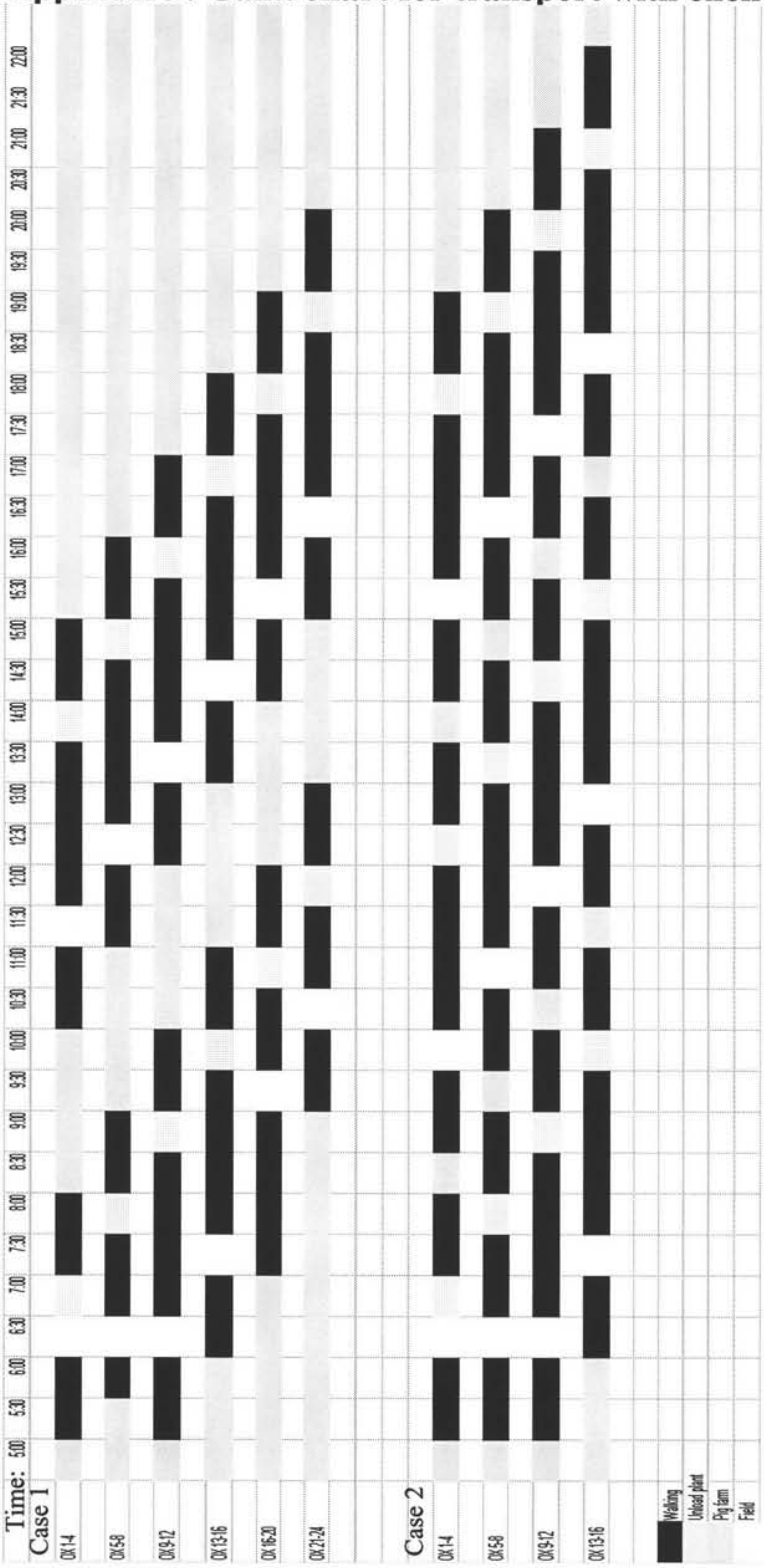
Appendix 8-2b: Hazard and operability study analysis for ethanol production

Guide Word	Deviation	Possible Causes	Consequences	Action Required
NO	No flow of sugar water into fermentor when filling	1) No sugar water available	No fermentation and no ethanol for distillation	a) Ensure good communication with farms b) b) Install level control with alarm
		2) Pump failure	same as for 1)	see b)
		3) Line blocked	same as for 1) and pump overheats	c) install heat control on pump
		4) Line ruptured	same as for 1) and leakage of sugar water into the plant	see b) d) good maintenance and/or inspection
		5) Storage vessel ruptured	same as for 1) and leakage of sugar water into the plant	see b) and d) e) Place storage vessel in a diked area
	No CO2 flow out of fermentor during fermentation	6) Pump failure	CO2 build-up, pressure increase, chance of fermentor rupture	f) Install pressure control in fermentor g) Make burst disc in fermentor
		7) Line blocked	Same as for 6) and pump overheats	see c), f) and g)
		8) No fermentation	See below at **no reaction**	see below at **no reaction**
	No flow out of fermentor during emptying	9) Pump failure	No flow to storage before distillation, chance of empty distillation column	h) Install flow control with alarm i) Install emergency pump j) Create large enough vessel with enough stored material to keep distillation column going
		10) Line blocked	Same as for 9) and pump overheats	See h), i), j) and c)
	No reaction	11) Poisonous substances present	No ethanol produced	k) Quality control on sugar- and dilution water, combined with a) and d) and j)
		12) No sugar water present	see 11)	see 1) to 5)
		13) No yeast present	see 11)	l) Ensure good control on yeast transfer from one batch to the next one m) store enough yeast for new batch

Guide Word	Deviation	Possible Causes	Consequences	Action Required
	No mixing	14) Stirrer broken	Large differences in local conditions in the fermentor, which result in lower ethanol production, formation of other products and yeast starvation	n) proper stirrer construction, see d)
MORE	More flow into fermentor when filling	15) Pump failure 16) High level control in fermentor offline	fermentor content flows out through the CO_2 tubes see 15)	see b) see d)
	More pressure	17) see 6) and 7)	see 6)	see f)
	More temperature in storage and/ore fermentor	18) Direct sunlight or high outside temperature 19) Fire	Increased chance of microbial growth in the storage tank (at 40% sugar not very likely) Chance of storage tank rupture	o) Install heat sensors and cooling p) Install a light source and light detecting sensors in the storage tank (microbes will scatter the light) q) Educate and equip a fire brigade at the plant and see o)
	More temperature in fermentor	20) Cooling water not cold enough 21) Flow rate not sufficient	Decreased reaction rate, more by-products formed, decay of yeast see 20)	r) Install temperature sensors in the water intake s) Adapt flow rate of cooling water t) Add enough pure ethanol to stop all fermentation
	More oxygen in fermentor	22) Leak in fermentor 23) Valve not closed	High yeast production and no alcohol production see 22)	u) Install dissolved oxygen tension sensor with alarm in the fermentor v) install valve position sensors with alarm
LESS	Less flow into fermentor when filling	24) Leakage in filling pipe	Leakage of sugar water into the plant	see b) and d)

Guide Word	Deviation	Possible Causes	Consequences	Action Required
	Less reaction	25) Not enough yeast present	Less ethanol production	see l) and m)
		26) Other biomass present	see 25) and more by products formed	see l) m) and although complete asepsis is not needed, train personnel to be hygienic
		27) Inhibitors present	see 25)	see l) m) and a)
	Less temperature in fermentor	28) no or less reaction	see **no** and **less reaction**	see **no** and **less reaction**
		29) too cold cooling water/to high flow rate	Less reaction	see r) and s)
AS WELL AS	Proteins present	30) Separation problems at the farms	Too much proteins gives a large layer of foam in the fermentor which could exit the fermentor trough the CO2 tubes	see a) and in the case it happens, anti foaming agents must be added
EARLY	Too early emptying of fermentor	31) Sensor error	Low concentration ethanol produced	see d) and t) make sure that the connection to the storage vessel is only opened when the fermentation is done well, else store the liquid in another vessel to pump back to the fermentor
		32) Miscommunication	see 31)	see d) and give the operators a good education

Appendix 9: Gantt chart for transport with oxen



Appendix 10.1: Pig farms and their distribution

Pig fed amount in 2001: amount on hand: 457,430,000; amount of sale 549,367,000. As shown in table 3 below, most of pig feed farms are located in the agricultural regions, account for 94.5%, comparing with other two regions: Three Big Cities, 2.5% and Pastoral region, 3.0%. And in the agricultural regions, the middle and lower reaches of Changjiang River produce 43.8□ in total amount pigs, while North China 21.6%, East North 6.3%, South East coastal zone 6.3%.

Table A10.1: Farm numbers

Based on annual amount of sale, 2001							
	1	2	3	4	5	6	
Farm size	50-90	100-499	500-2999	3000-9999	10000-50000	>50000	Total
Number of farms	703,777	193,450	22,956	2,798	747	16	923,744
%	76.2	20.9	2.5	0.3	0.1	0.0	100.0

Table A10.2: Farms regionalized distribution

		1	2	3	4	5	6
Farm size		50-90	100-499	500-2999	3000-9999	10000-5000	Above 50000
Farm distribution %							
BJ, TJ, SH		2.5	6.4	7.2	17.2	25.9	9.1
Agricultural region (Total)		94.5	91.8	90.8	81.2	73.5	90.9
	1	16.5	15.0	14.4	9.0	8.0	27.3
	2	20.1	16.6	9.5	7.3	5.7	0.0
	3	43.1	43.6	42.8	35.7	30.	18.2
	4	9.2	13.4	20.9	26.9	28.0	36.4
	5	5.5	3.2	3.2	1.8	1.1	9.1
Pastoral region		3.0	1.8	2.0	1.5	0.7	0.0
Total		100	100	100	100	100	100
1 North China; 2 East North China; 3 the middle and lower reaches of Changjiang River; 4, South China; 5 West South China; BJ- Beijing; TJ-TianJing; SH-ShangHai							

Appendix 10-2: Wages in China

The minimum wage rate in China:

- North--€17(140 RMB) per month in urban areas, €12(100 RMB) per month in rural regions;
- South--€34(280 RMB) per month in urban areas, €25(210RMB) per month in rural regions.

Future of the grassland product in China

The aim of meat productivity at 2010 is $6.5 \cdot 10^{8}$kg meat per year, need feed resource about $7.68 \cdot 10^{12}$kg, grass feedstuff about $20 \cdot 10^{12}$kg, which including 10^{12}kg cultivated grassland, and $3 \cdot 10^{12}$kg nature grassland. If in the feed mixture, the grass powder content is about 5-10%, then this needs 305·108-610·108kg high quality grass powder.

Appendix 10-3: Grassland information for the Qing Hai province

Qing Hai province: [1]
Nature grassland: totally $3.645 \cdot 10^{12}[m^2]$, which is about one of tenth of the whole country's grassland area. 86.7% of total grassland is useable which area is $3.160 \cdot 10^{12}[m^2]$. 49.92% is used in the winter and spring, 50.08% is used in the summer and autumn. The average fresh grass productivity is about $2.53[kg/m^2]$ and the total productivity is about $7.96 \cdot 10^{11}[kg]$.
Characteristics of the grassland:

1. 65.06% of the whole grassland is the high-cold meadow grass.
2. The proportion of Legume is small; Sedge and the Standing Grain are the predominant grass. The area of Legume is about 4.6%, the Sedge and the Standing Grain is about 90.03%.
3. Contents: (dry matter)
   Protein: > 13%-- Legume; > 10.86% -- Standing Grain
   Fat: > 2%
   Sugar: > 40%
   Fiber: > 35%

There are 2548 communities in the agriculture area (about 85% of them have high ways). About 1554 communities are in the pasture area (70% of them have highways or motor vehicles).

Reference:
[1] http://www.nmg114.com/corporation/nmgzz.htm

Appendix 10-4: Productivity of Grasslands in China

Grass type	Productivity □kg/1000m^2□	Total productivity□10^8□	Proportion (%)
Tropic brushwood	2,544	6490	21.56
Swamp	2,183	492	1.63
Whole country	911	30106	100
Warm grassland	889	5888	19.56
Warm brushwood	740	2710	9.03
Warm-Sand grassland	360	1432	4.76
High-Cold grassland	273	1341	4.45
Meadow	119	11288	37.49
High-Cold-Sand grassland	117	65	0.22

* Sorted by the amount of productivity

Appendix 10-5: Example of plant in China

Produce feed cake for non-vegetarian livestock from corn stalks in Hebei Province, China:
Total investment: 90,000 euro
Occupied area for process: 270 [m^2]
Occupied area for cutting and drying in field: 4200[m^2]
Corn Stalk price (gathered from farmers): 6 euro per ton
Production rate: 1.2 – 1.8 ton per hour
Production cost: 20 euro/ton
Product price: 30 euro/ton
Number of labourers: 30
Market: Inner Mongolia, Shanghai, etc. [1]

Reference:

[1] http://www.amic.agri.gov.cn/pages/infopage.asp?ino=4272

Appendix 11-1: Calculation of the economic situation of the process

The calculations are based on equations form Coulson and Richardson, volume 6, chapter 6.

First, the fixed capital costs are calculated. The fixed capital costs are based on the major equipment costs. The costs for the other equipment are calculated with some factors, called Lang factors. All major equipment is given in table A11-1. The total costs are € 1,866,200 (PCE).

Table A11-1: Equipment costs for small-scale scenario

Equipment costs		
Name	Capital Costs [€]	Reference
A01	100,000	Chapter 8.1.3
E01	21,000	Chapter 8.2.1
E02	6,200	Chapter 8.4
E03	32,000	Chapter 8.4
F01	37,000	Chapter 8.4
R01	132,000	Chapter 8.3.2
R02	562,500	Chapter 8.3.4
S01	220,000	Chapter 8.1.4
S02	2,400	Chapter 8.3.3
S03	15,600	Chapter 8.3.3
T01	15,200	Chapter 8.1.1
T02	75,100	Chapter 8.1.5
T03	89,000	Chapter 8.3.3
T04	26,500	Chapter 8.3.4
T05	226,800	Chapter 8.2.3
V01	4,000	Chapter 8.1.2
V02	4,000	Chapter 8.1.3
V03	15,500	Chapter 8.3.4
X01	34,000	Chapter 8.1.2
X02	8,500	Chapter 8.1.2
X03	16,900	Chapter 8.1.2
X04	36,700	Chapter 8.1.3
X05	27,000	Chapter 8.2.2
X06	127,000	Chapter 8.1.5
X07	31,300	Chapter 8.3.2
TOTAL	1,866,200	

From table 6.1 the Lang factor can be calculated. Because the process contains solids and liquids, the middle column is used. Because no utilities are needed, f_6 is not taken into account. Storage is already added in the PCE, so f_7 is also not used. Leaving these two out, the Lang factor will be 2.5. This will give a PPC of € 4,665,500.

PPC = PCE*f-factor eq.A11-1

Indirect Costs = $PPC*(f_{10}+f_{11}+f_{12})$ eq.A11-2

Fixed Capital = $PPC*(1+f_{10}+f_{11}+f_{12})$ or eq.A11-3

Fixed capital = PPC + indirect costs

The fixed capital cost is equal to the PPC multiplied with a factor for the indirect costs. The indirect costs are set at 40% of the PPC. The fixed capital costs are € 6,500,000.

The fixed capital cost is only part of the total investment costs. The Total Investment Costs also contain Working Capital (storage of products, given credits) and Licences. From the PSD-course assignment 7 (CE3801), the fixed capital costs were 80% of the Total Investment Costs. Assuming for this process it is the same, the Total investment Costs are € 8.2 million.

For the Ethanol production scenario, same calculations are used. Extra equipment costs are listed in table A11-2.

Table A11-2: Equipment costs for ethanol producing scenario

Equipment costs		
Name	Capital Costs [€]	Reference
WaterEth	1,610,000	Chapter 8.6
Packing	770,000	Chapter 8.6
Total heat exchangers	200,000	Chapter 8.6
Membrane	180,000	Chapter 8.6
Zeolite vessel A	11,800	Chapter 8.6
Zeolite vessel B	11,800	Chapter 8.6
Zeolite vessel C	11,800	Chapter 8.6
Zeolite vessel D	11,800	Chapter 8.6
Zeolite	400	Chapter 8.6
Fermentor	2,000,000	Chapter 8.6
Rotary drum	1,500,000	Chapter 8.6
Incoming storage A	122,000	Chapter 8.6
Incoming storage B	122,000	Chapter 8.6
Incoming storage C	122,000	Chapter 8.6
Reactor out storage	38,000	Chapter 8.6
Ethanol storage	4,600	Chapter 8.6
TOTAL	6,716,200	

Appendix 11-2: Calculations on Operating Costs

The numbers refer to table 14-2 and 14-4 in chapter 14.

Ad 1. Raw materials
17,000 ton of Legumes per year * € 21.28 per ton (Chapter 5)

Ad 2. Miscellaneous Materials
10% of the maintenance

Ad 3. Utilities
None

Ad 4. Packaging and shipping
All products are transported without packaging. Transportation is done with oxen, so no costs for shipping.

Ad 5. Maintenance
6% of Fixed capital

Ad6. Operating Labour

Table A11-3: Operating costs during the 180 days in production season

	Persons per shift	***Shifts per day***	***Hour work per shift***	***Costs per person per shift €***	***Total Labour costs per day €***
Transport	24	2	5	1.50	72
Operators	7	3	8	3.00	63

The costs for harvesting are already in the legume price.

Ad 7. Laboratory Costs
20% of Operating Labour

Ad 8. Supervision
20% of Operating Labour

Ad 9. Plant overheads
50% of Operating Labour

Ad 10. Capital Charges
15% of Fixed capital

Ad 11. Insurance
1% of Fixed capital

Ad 12. Local taxes
2% of Fixed capital

Ad 13. Royalties
1% of Fixed capital

Ad 14-16. Sales Expenses, General overheads and Research + Development
20% of the direct production costs

Appendix 12-1: The 19 PIQUAR criteria

	L. Petrus	J. Sanders	Christa	Jeffery	Shanfeng	Shengbin	Tiany	Tobias	participators		Total	AVERAGE	
Factors	2	2	1	1	1	1	1	1					
Criteria													
minimal investment cost	8	9	8	9	10	9	9	10	10	I	89	8.9	A
based on proven technology		7				7	5	8	5	V	34	6.8	J
comply with environmental legislation	9		6		7				4		31	7.75	
heat integration		9	7			7	7		5	V	39	7.8	H
internal recycling of wastes		6		8	8		8	1	6	IV	37	6.166667	F
no emission to soil	8						6		3		22	7.333333	
product quality and quantity	9				7				3		25	8.333333	
labor safety aspects		1	8	4	5				5	V	19	3.8	
constraints	8				5		7		4		28	7	
goal of the process must be clear in advance	8		7	8	9	7		9	7	III	56	8	D
relationships with local authorities		2	7	3		6			5	V	20	4	
stable operation	8		8		8	7	8	6	7	III	53	7.571429	E
trusted by people living nearby	8		8	7	7	8	6	5	8	II	57	7.125	B
via feedstock and product flows	8		9					3	4		28	7	
low production cost of endproduct	8	3		7		7	7	4	8	II	47	5.875	C
specification is met	8					8	7		4		31	7.75	
food/feed safety		4		3					3		11	3.666667	
demand driven		10		5		7		7	5	V	39	7.8	I
potential for further developments determined		5	7	2	4			2	6	IV	25	4.166667	G

Appendix 12-2: Determination of the weighing factors of the PIQUAR criteria

Determination of the 10 most important criteria

Before the first meeting with the principals (kick-off meeting), the group members picked criteria that were relevant or useful for this project from the list given with PIQUAR. Everybody could vote as many criteria as he or she saw fit and all criteria with 4 or more (out of a maximum of 7) votes were presented at the kick-off meeting to the principals. In the week after the kick-off meeting the principals assigned a number between 1 (bit important) and 10 (very important) to ten of these criteria. They also had the opportunity to add new criteria and rate those too, which one of the principals did. One principal rated 11 instead of 10 criteria, but this does not matter for applying PIQUAR. Two identical criteria were voted by both principals, which left 19 different criteria from the original list. All team members voted on ten of these criteria with a number between 1 (bit important) to 10 (very important). The resulting list is shown in appendix 12-1.

To be able to apply PIQUAR, ten criteria must be chosen and ranked. From the 19 criteria left, first the ones with the most votes were chosen (the number of the vote was not taken into account yet), where the votes of the principals counted double. In appendix 12-1 it is shown that several criteria had the same amount of votes. In these cases the average numbers of the votes were taken into account. This resulted in the following list of 10 criteria, with the most important one on top, and the least important one of the important ones as last:

Table A12-1: List of the chosen criteria

	Criterion
A	minimal investment cost
B	trusted by people living nearby
C	low production cost of end product
D	goal of the process must be clear in advance
E	stable operation
F	internal recycling of wastes
G	potential for further developments determined
H	demand driven
I	heat integration
J	based on proven technology

Determination of the weighing factors

In order to make weighing factors for the criteria, a pair wise comparison matrix must be constructed. This matrix is a reciprocal matrix, meaning that $a_{ij} = 1/a_{ji}$. A number between 1 and 9 must be given, with the following meaning:

1: equally important criteria
3: the criterion in the row has a weak importance over the criterion in the column
5: the criterion in the row is strongly more important than the criterion in the column
7: the criterion in the row is extremely more important than the criterion in the column
9: the criterion in the row is absolute more important than the criterion in the column

Since it was judged that all chosen criteria were really important and no criteria was extremely more important than any other, no numbers lower than 6 were used in the matrix. The numbers were chosen based both on the marks given to the criteria and on the total amount of votes they received. This resulted in the following matrix:

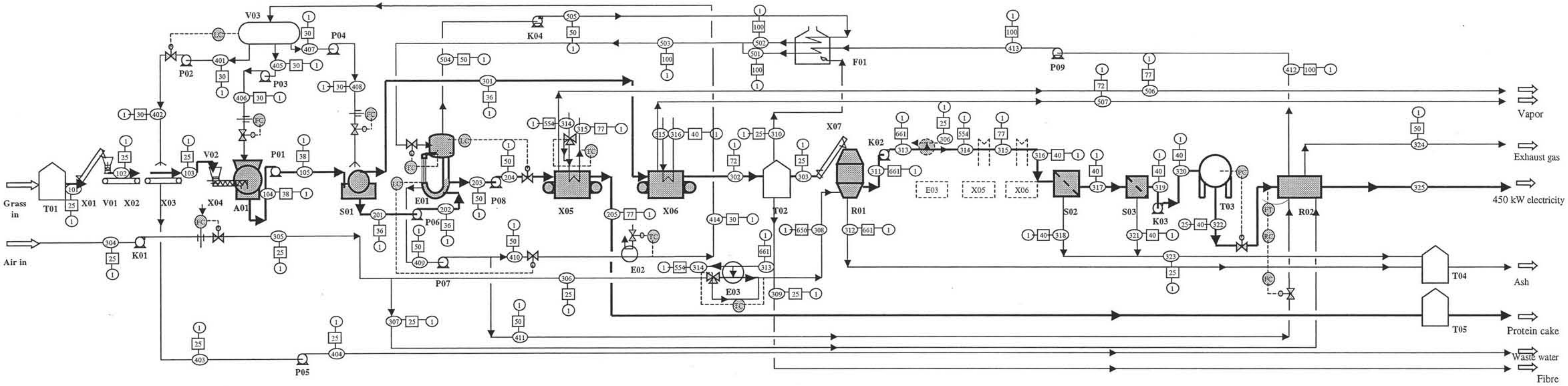
	A	B	C	D	E	F	G	H	I	J
A	1,00	3,00	3,50	4,00	4,00	4,50	5,00	5,50	5,50	6,00
B	0,33	1,00	1,50	2,00	2,50	4,00	4,50	4,50	4,50	5,00
C	0,29	0,67	1,00	1,50	2,00	3,00	3,50	4,00	4,00	4,50
D	0,25	0,50	0,67	1,00	1,50	2,50	3,00	3,50	3,50	4,00
E	0,25	0,40	0,50	0,67	1,00	2,50	3,00	3,50	3,50	4,00
F	0,22	0,25	0,40	0,40	0,40	1,00	2,00	2,50	2,50	3,00
G	0,20	0,22	0,33	0,33	0,33	0,50	1,00	2,00	2,00	2,50
H	0,18	0,22	0,29	0,29	0,29	0,40	0,50	1,00	1,50	2,00
I	0,18	0,22	0,29	0,29	0,29	0,40	0,50	0,67	1,00	2,00
J	0,17	0,20	0,25	0,25	0,25	0,33	0,40	0,50	0,50	1,00

In order to get the weighing factors from this matrix, the eigenvalues and eigenvectors are needed. This was done with the help of the program MatLab ®. The command **`[eigenvalues, eigenvectors] = eig(A)`** was given, which returned the eigenvectors of matrix A with the corresponding eigenvalues. From the 10 eigenvalues, only 1 was close to 1, which meant that the eigenvector corresponding to that eigenvalue contained the information for the weighing factors. Every element in this vector must be divided by the sum of all the elements in the vector. And this gave the following weighing factors for the selected 10 criteria:

Table A12-2: Weighing factors for the PIQUAR criteria

	Criterion	Weighing factor
A	minimal investment cost	0,29
B	trusted by people living nearby	0,17
C	low production cost of end product	0,13
D	goal of the process must be clear in advance	0,11
E	stable operation	0,10
F	internal recycling of wastes	0,06
G	potential for further developments determined	0,05
H	demand driven	0,04
I	heat integration	0,03
J	based on proven technology	0,03

An alternative way to get the same result for the weighing factors is to divide every element in every column with the sum of the elements of that column and than take the average of each row.



Process Equipment Summary

A01 : Disc refiner	K04: Blower stream 504	P08 : Pump after E01	T02 : Fibre storage after X06	X02: Transport belt after V01
E01 : Evaporator	P01 : Pump after A01	P09 : Pump stream 415	T03 : Gas storage	X03: Transport belt after X02
E02 : Condensor below X06	P02 : Pump stream 401	R01 : Gasifier	T04 : Ash storage	X04: Transport screw
E03 : Heat exchanger below T02	P03 : Pump stream 405	R02 : Gas engine 450kW	T05 : Protein cake storage	X05: Belt dryer after E01
F01 : Furnace	P04 : Pump stream 407	S01 : Rotary drum filter after A01	V01 : Hopper and Chopper	X06: Belt dryer after X05
K01 : Blower stream 304	P05 : Pump stream 403	S02 : Baghouse	V02 : Balance	X07: Elevator before R01
K02 : Blower after R01	P06 : Pump stream 201	S03 : Cartridge filter	V03 : Recycled water buffer tank	
K03 : Blower after S04	P07 : Pump stream 409	T01 : Grass storage	X01 : Elevator after T01	

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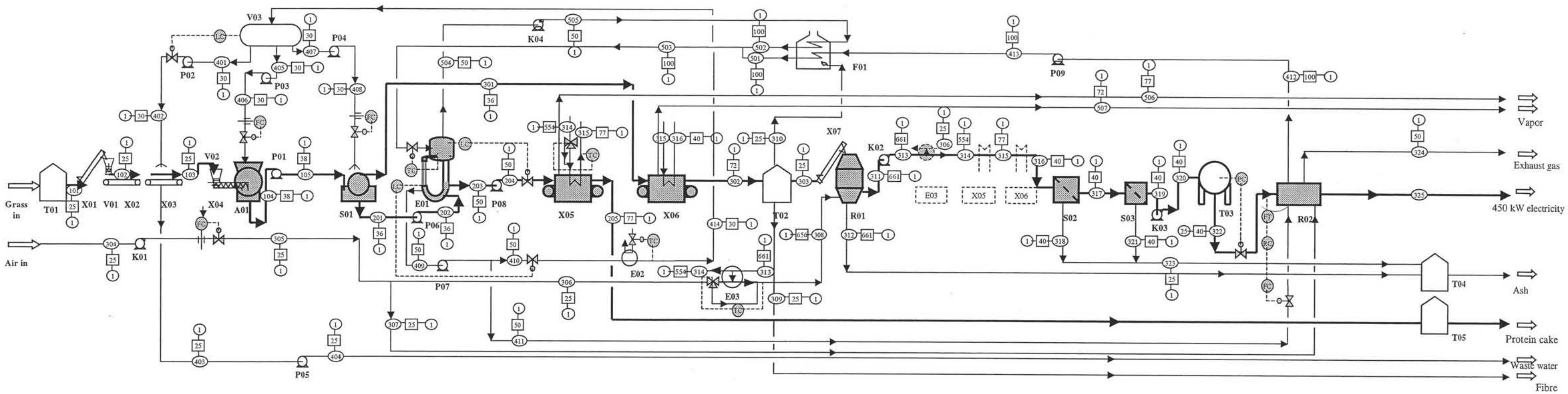
Process Flow Scheme

Project : A process to refine green plants – From grass to protein cakes and useful energy source

Proj. ID Number : **CPD3295**

Completion Date : December 15th, 2003

Stream number (ellipse) | Temp (°C) (square) | Pressure (Bara) (circle)



Process Equipment Summary

A01 : Disc refiner
E01 : Evaporator
E02 : Condensor below X06
E03 : Heat exchanger below T02
F01 : Furnace
K01 : Blower stream 304
K02 : Blower after R01
K03 : Blower after S04
K04 : Blower stream 504
P01 : Pump after A01
P02 : Pump stream 401
P03 : Pump stream 405
P04 : Pump stream 407
P05 : Pump stream 403
P06 : Pump stream 201
P07 : Pump stream 409
P08 : Pump after E01
P09 : Pump stream 415
R01 : Gasifier
R02 : Gas engine 450kW
S01 : Rotary drum filter after A01
S02 : Baghouse
S03 : Cartridge filter
T01 : Grass storage
T02 : Fibre storage after X06
T03 : Gas storage
T04 : Ash storage
T05 : Protein cake storage
V01 : Hopper and Chopper
V02 : Balance
V03 : Recycled water buffer tank
X01 : Elevator after T01
X02: Transport belt after V01
X03: Transport belt after X02
X04: Transport screw
X05: Belt dryer after E01
X06: Belt dryer after X05
X07: Elevator before R01

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