Techno-Economic Analysis for Papermaking from Bagasse as a Value Addition Strategy

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The pulp and paper manufacturing industry Zimbabwe relies heavily on importing waste paper as its raw material from neighbouring countries such as South Africa. At the same time, the available local resource is wood, the continual cutting of which results in environmental problems. As a measure to add value and beneficiation of the sugarcane bagasse as well as to reduce deforestation, there is need to use alternative raw materials such as bagasse, which is readily available at sugar plantations for paper production. This study involved the processing of 40 tons per day of virgin paper from bagasse as an alternative option, using the kraft process with a conversion yield of 35%. Using this process, optimum operating pressure and temperature were found to be 9.6 atmospheres and 200 ^{o}C respectively, and a detailed process design was done considering the process safety issues. After doing an environmental impact assessment, the bagasse to virgin paper plant was recommended for siting in Chiredzi, Zimbabwe. An economic analysis carried out indicated a return on investment of 45% and a payback period of 2.2 years. The net present value was found to be $758,000 with the virgin paper selling price set at $108/ton. According to these assessments, the project is judged to be technically and economically feasible.

Keywords: Bagasse; Kraft process; Virgin paper; Value addition; Techno-economic analysis

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INTRODUCTION

The pulp and paper industry in Zimbabwe relies heavily on importing waste paper as raw material. In addition, alternative sources from fresh wood are also being utilised. These practices pose both economic and environmental challenges to paper mills, as it is now costly to produce the paper, thereby increasing the product price on the market. At the same time, the sugar industry is generating huge amounts of bagasse as a waste product, which has potential to be used in paper production (Samariha and Khakifirooz 2011). The use of bagasse in the making of virgin paper is considered to be more environmentally friendly than using wood because of less harmful chemicals that are used in the production process (Gupta and Ahuja. 1989; Covey *et al*. 2006). Bagasse is the fibrous material that remains after crushing sugar cane and extracting the sugar. Bagasse fiber consists mainly of cellulose, lignin, and hemicellulose, is widely used for paper manufacture (Gupta and Ahuja 1989; Rainey and Clark 2004). Introducing bagasse-based virgin fiber as a components of the paper tends to reduce the dependence on imported waste; also the cutting down of trees can be reduced, further decreasing environmental impacts. The pulp paper processing is done in the following stages: cooking, pulp washing, pulp screening, pulp cleaning, pulp thickening, and bleaching (Lam *et al*. 2004; Poopak and Reza 2012). In Zimbabwe, the sugar industry is generating 0.427 million tons per year of bagasse as a waste by-product (Mtunzi *et al*. 2012). This led to an innovative plant design capable of achieving 40 tons per day production of virgin paper from bagasse. The product had involved a value-addition strategy with a main focus on determining the economic viability of this technology (Nemati *et al*. 2011). The techno-economic assessment allowed the potential application of the process at industrial scale.

EXPERIMENTAL

A sample of bagasse (Fig. 1) was obtained from Green Fuels Private Limited's Chisumbanje Plant, located in the Lowveld in Zimbabwe. This sample was analyzed at the Harare Institute of Technology's Chemical and Process Systems Engineering laboratory utilizing the available resources. Feasibility of producing the non-virgin paper from bagasse and determining its characteristics were done.

Fig. 1. Sample of bagasse used in non-virgin paper production in this study

Determination of Non-Virgin Paper Production Feasibility from Bagasse

The materials used included bagasse, NaOH, Na_2S, a blender, a hot plate, a set of sieves, an oven, a plastic dish, a sponge, nylon cloth, and water. To begin, 30 g of bagasse was weighed on an electronic balance. Then 3 g of NaOH and 3 g of Na_2S were added to a large glass beaker containing 500 mL of water, and the resulting mixture was stirred. The mixture was boiled for a minimum of two hours using a hot plate. After cooking, the cooked pulp was placed in a blender to produce a fine pulp. The pulp was poured onto a sieve and swished. This was done to evenly distribute the bagasse pulp. The pulp was placed on a nylon cloth, and a sponge used to evenly press over the pulp so as to draw as much moisture out of the pulp as possible. A rectangular wood block was placed on top of the nylon cloth. The sieve was turned upside-down to remove the paper from the sieve. The paper was left on the tray on top of the nylon cloth and left to dry overnight at 70°C.

Determination of Residence Time for Non-Virgin Papermaking

100g of NaOH and 100 mL of Na_2S were added respectively in 1 L of water. Then 500 g of bagasse was weighed and placed in a beaker. The white liquor was added to the bagasse sample and the mixture was boiled at 100 ^oC and atmospheric pressure. The conductivity of the cooking pulp was tested at regular intervals and the readings recorded.

Determination of Absorbency

The capillary action test was employed as a measure of absorbency. The materials used included samples of produced paper, water, acetone, hexane, methanol, ethyl ether, beaker, and a clamp holder. The paper was cut into rectangular strips of equal dimensions and each strip marked with an ink drop at the middle. The strips were dipped into various solvents with the ink drops remaining above the surface of the solvent following the paper chromatography procedure. The distance moved by the ink drop after a fixed time of five minutes was noted, and the speeds of the various solvents in the paper were calculated.

Determination of Virgin Paper Biodegradability

An electronic balance, flash bottles, pieces of same paper sizes, micro bacteria, water, and an oven were used. Five pieces of the paper were weighed using a balance to note their initial masses. These specimen pieces were immersed in flash bottles containing micro bacteria. These bacteria produced an alkaline solution that digests and breaks down the cellulose in the paper. Samples were left in the flash bottles for five days then harvested. The harvested samples were washed using water and dried overnight in an oven and reduction in mass was noted as the measure for biodegradability.

Determination of the Effect of Various Pulping Chemicals on the Cooking Rate

Four samples of bagasse were subjected to different combinations of NaOH, Na_2S and Na_2CO_3 reagents to determine the effect of the chemicals on the rate of pulping. The different combinations of chemicals were used and labelled as experiment 1, 2, 3 and 4. Experiment 1 had both Na_2CO_3 and sulphide present with NaOH absent; Experiment 2 had both hydroxide and carbonate present with Na_2S absent; Experiment 3 had both Na_2S and hydroxide present with Na_2CO_3 absent and Experiment 4 had all test reagents present.

RESULTS AND DISCUSSION

The bagasse was characterized for cellulose, lignin and ash content which are key in paper production. The characterization of the bagasse used is given in Table 1.

Table 1. Bagasse Characterization

Component	% Composition
Cellulose and hemicellulose	53.35 ± 0.8
Lignin	22.50 ± 1.9
Extractives soluble in alcohol-acetone	4.75 ± 4.6
Ash content	1.92 ± 3.8

Feasibility Test of Kraft Process Using Bagasse

A sheet of virgin paper from bagasse was produced with a conversion yield of 35% (Fig. 2). The experiment was also used to test the various effects of chemicals on the pulping process to aid in reagent selection and to determine the yield of the process. The yield of the process was between 35 and 40%, indicating that the pulping and washing was done thoroughly.

Fig. 2. Raw non-virgin paper produced from sugar cane bagasse in the laboratory

Effects of Various Chemicals on the Pulping of Bagasse

Four samples of bagasse were subjected to different combinations of reagents to determine the effect of the chemicals on the rate of pulping. The different combinations of chemicals were used and labelled as Experiments 1, 2, 3 and 4 (Table 2). In Experiment 1, NaOH was absent to de-lignify the bagasse and so mechanical degradation by the blender to produce pulp was very difficult. In Experiment 2, NaOH alone was present, and a greyish mixture of unreacted bagasse and pulp was observed. In Experiment 3, the bagasse took a long time to react, with periodic vigorous stirring. In Experiment 4, the pulping was easier. The purpose of NaOH is to degrade lignin and that of Na_2S is to accelerate the cooking reactions and to decrease cellulose degradation caused by NaOH. The greyish colour and lumpy pulp obtained in Experiment 2 is an indication that the mixture was not cooked, and hence the pulping process was quite difficult. An absence of any of the three reagents showed difficulty of pulping process. All specified pulping chemicals: NaOH, Na_2S, and Na_2CO_3, must be added during the cooking process in order to obtain a good pulp. Any compromise in the quantities used will also result in a compromised quality of the pulp produced.

Table 2. Effect of Various Chemicals on the Pulping of Bagasse Paper

Experiment	NaOH	Na_2S	Na_2CO_3	Result
1	Absent	Present	Present	The bagasse could not be mechanically pulped by the blender
2	Present	Absent	Present	A greyish mixture of unreacted bagasse and pulp was obtained
3	Present	Present	Absent	The bagasse took a long time to react with vigorous stirring periodically
4	Present	Present	Present	The bagasse was chemically weakened and easily mechanically blended

Biodegradability Test

The results of this method permit an estimation of the degree of 0.44% on the biodegradability and over which the paper 227.3 days will remain in an aerobic environment. This is done by measuring reduction in mass as a function of time that the paper is exposed to micro bacteria (Table 3). The paper is estimated to be fully degraded after 7.6 months. The results showed that the paper is biodegradable thus production of virgin paper from bagasse is a green solution to environmental and pollution management.

Table 3. Biodegradability Results on Virgin Paper from Bagasse

Sample	Initial mass, M_1(g)	Final mass, M_2(g)	Difference in mass, $M_1 - M_2$	$\frac{M_1 - M_2}{M_1}$	BD (%)
1	3.78	3.74	0.04	0.010	1.10
2	3.65	3.61	0.04	0.010	1.10
3	3.74	3.68	0.06	0.016	1.60
4	3.60	3.52	0.08	0.022	2.20
5	3.56	3.50	0.06	0.017	1.70

Capillary Action Test

This a test used to measure the absorbency of the paper. Distance moved by the ink drop in the specified time was used to calculate the speeds of the various solvents in the paper. The other solvents were used to compare with water (Fig. 3). The resulted show that acetone had the highest rate of capillary action, followed by methanol, water, hexane, and ethyl ether. This indicated that virgin paper made from bagasse has good absorbency and can be used for toiletry purposes.

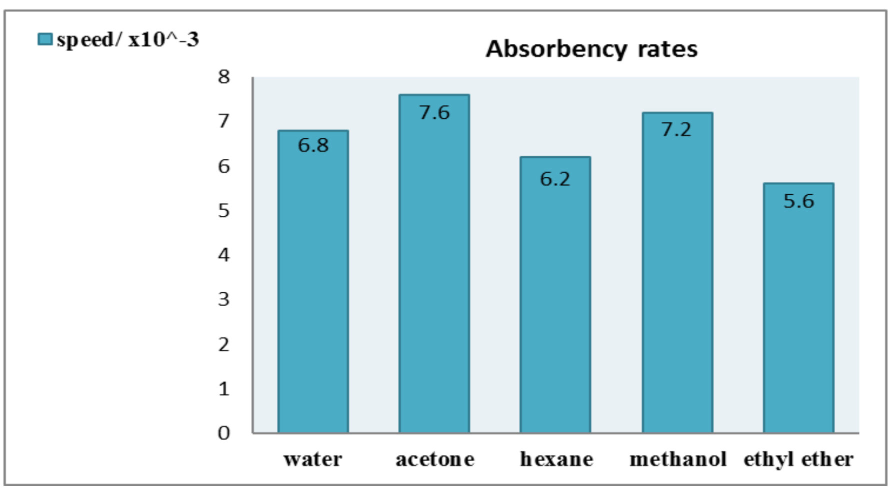

Fig. 3. Capillary action results indicating paper absorbency

Determination of Residence Time in Pulper through the Electrical Conductivity

The electrical conductivity of the pulp at any given time is used as a measure to show the amount of unreacted NaOH in the pulp. The pulping process was complete when the conductivity of the pulp is 2 μS/cm at a residence time of 120 minutes (Fig. 4).

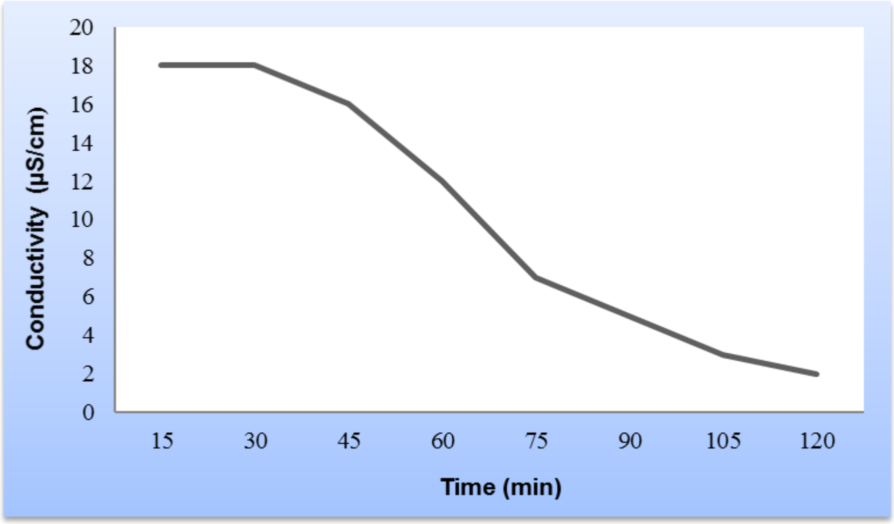

Fig. 4. Residence time of pulping

PROCESS DESIGN DESCRIPTION

The pulp paper process makes use of the kraft pulping technique (Gupta and Ahuja 1989; Rainey and Clark 2004), as diagramed in Fig. 5.

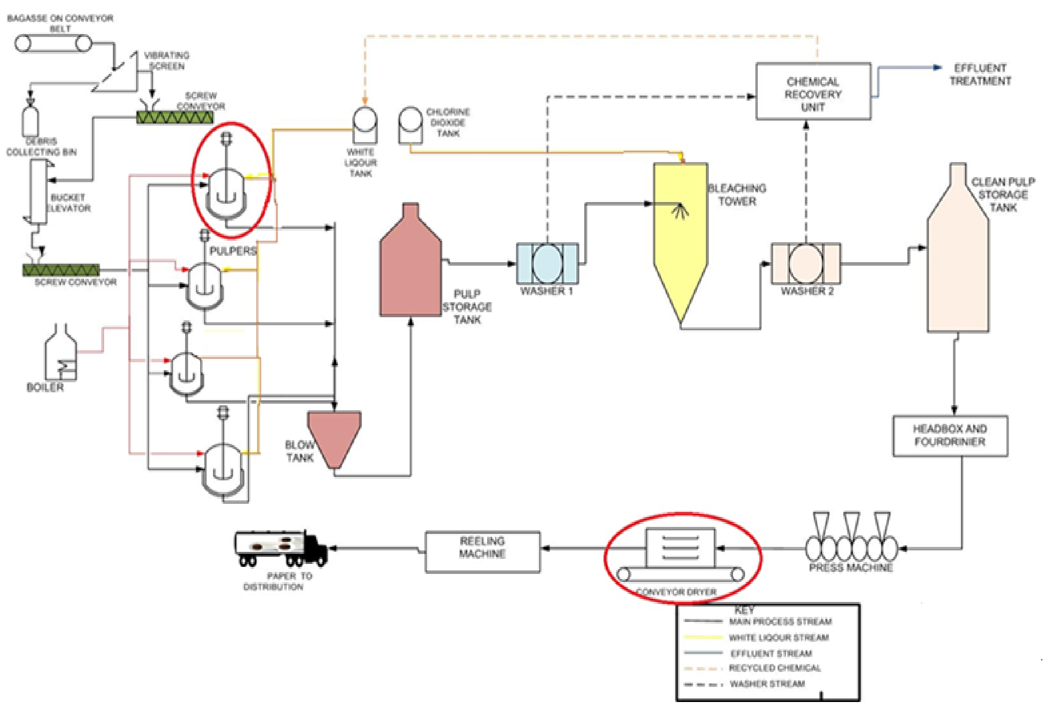

Fig. 5. Process flow diagram for virgin paper processing plant from bagasse

Before kraft pulping, the bagasse is passed over a vibrating screen to remove particles such as stones, which might cause damage to equipment if present as well as compromise the quality of the pulp. The bagasse is then cooked in a solution known as white liquor containing water, NaOH, and Na_2S at a pressure of 9.6 atm and 200^oC in a large vat known as a pulper (Gupta and Ahuja 1989; Rainey and Clark 2004). The resulting slurry known as pulp is pumped to the blow tank where it is defragmented by a sudden drop of pressure in the blow tank. The slurry is pumped to the storage tank. Screeners and washers then wash the pulp removing chemicals (contained in the black liquor) and other debris such as pith. The washed pulp is then bleached in bleaching towers using chlorine dioxide to give a white cleaner colour. The pulp is refined and is formed into a paper web by the headbox. The wet paper web is pressed by the press machine as preparation for drying by reducing the water content of the virgin paper to make the required product (Fig. 5). The virgin paper produced from bagasse can be further processed to newsprint, printing paper, tissues, or kraft paper, depending on the requirements of the customer. Process control and hazard operability analysis were done to ensure efficiency and safe operation of the plant by monitoring key variables such as flows, temperature, level, composition, and moisture content (Fig. 5).

Considering that an amount of wet bagasse recovered annually is 0.427 million tons per year with a yield of 35% and a plant utilisation of 80%, an overall mass balance per day indicated in Fig. 6 was carried out.

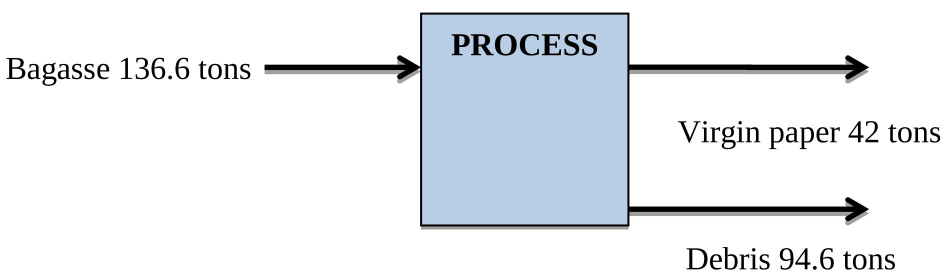

Fig. 6. Mass balance summary per day

An overall heat balance was carried out, considering that the energy required is equal to the heat into the process less the heat out. This analysis considered the batch pulper and the conveyer, as indicated in Table 4.

Table 4. Energy Balance Summary

Item	Heat in (MJ/ batch)	Heat Out (MJ/ batch)
Continuously stirred batch pulper	19 441	2700
Conveyor dryer	16 485	1 833

EQUIPMENT DESIGN

Equipment design of the continuously stirred batch pulper and conveyor dryer was carried out. Mass and energy balances assisted in the design of these two pieces of equipment as well as the sizing and specification of other equipment.

Stirred Batch Pulper Design

The main function of the stirred batch pulper (SBP) (Fig. 7) is to convert bagasse into pulp by breaking down lignin in bagasse fibers through cooking, thereby softening it for paper sheet formation. Bagasse is fed into the pulper by use of a screw conveyor and white liquor as well as water is pumped into the SBP. An agitator is used to keep contents well mixed for thorough cooking.Important parameters governing the SBP design are given in Table 5.

Table 5. Stirred Batch Pulper Design Specifications

CHEMICAL ENGINEERING DESIGN	
Number required	4
Height	4.34 m
Nominal diameter	2.17 m
Volume	16 m^3
Nominal pulper thickness	0.022 m
Number of heating coils	8.4
Design pressure	1 167 kPa
Jacket thickness	0.30 m
Material of construction	Carbon steel
MECHANICAL ENGINEERING DESIGN	
Weight of contents	1 876 kN
Maximum bending moment	21.3 kNm
Maximum compressive stress	1.931 kN
Wind load	1.572 kN

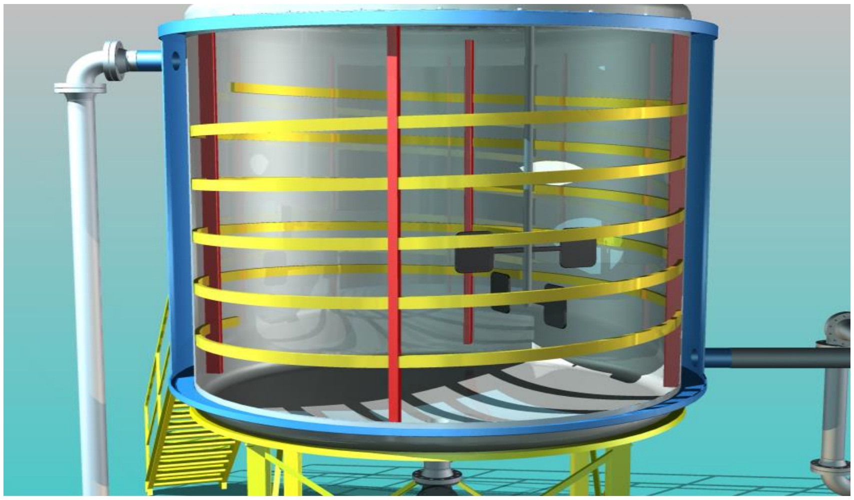

Fig. 7. Stirred batch pulper with cross section showing position of agitator drawn in Autocad 3

Conveyor Dryer Design

The conveyor dryer, also known as the continuous through-circulation dryer, operates on the principle of blowing hot air through a permeable bed of wet material passing continuously through the dryer (Fig. 8). Dryer rates are high because of the large area of contact and short distance of travel for the internal moisture. Conveying-screen dryers are fabricated with conveyor widths from 0.3 to 4.4 m sections. The important parameters that were calculated are the volume, area, slicing width, height, length, conveyor speed of belt, power required by blower, and heater-fan. An assumption of taking the maximum value of the dryer capacity was made in the design of the conveyor dryer. Important parameters governing the conveyor dryer design are given in Table 6.

Table 6. Conveyor Dryer Design Specifications

CHEMICAL ENGINEERING DESIGN	
Number required	1
Function	Drying of wet paper web into virgin paper
Operation	Continuous
Number of heater-fans	3
Area	18.14 m^2
Length	4.77 m
Slicing width	3.8 m
Height	3.8 m
Volume of dryer	69 m^3
Operating temperature	205^oC
Operating pressure	1 atmosphere
MECHANICAL ENGINEERING DESIGN	
Feed weight on belt	6.2 N
Maximum tensile stress on belt	137 N
Creep strength	581 kN

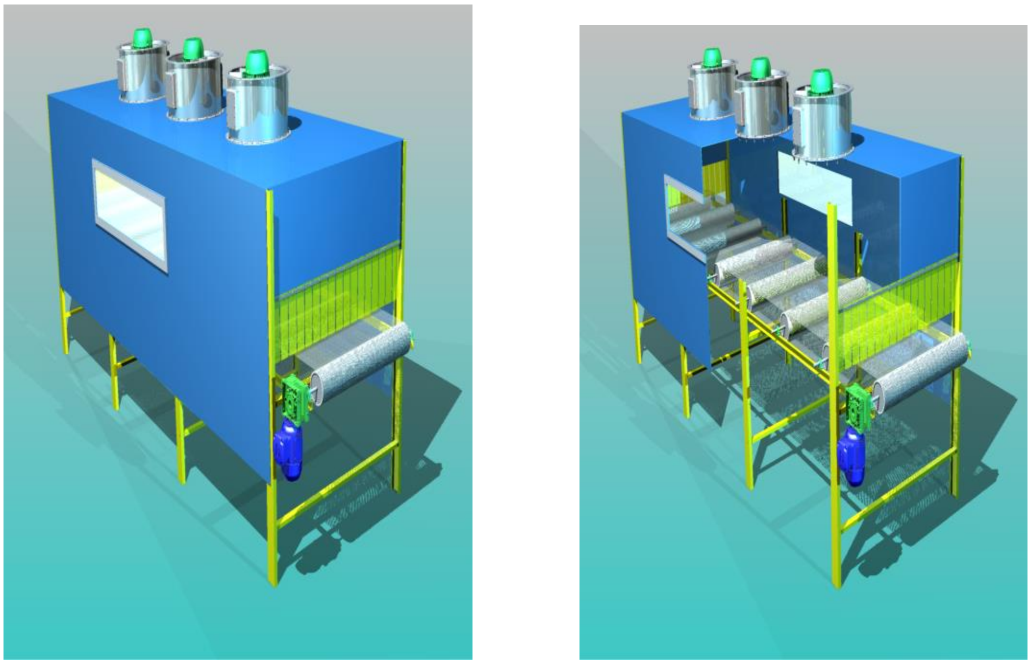

Fig. 8. Conveyor dryer (a) South east view, (b) Section view drawn in AutoCad 3

Sizing Major Equipment

Equipment in the process was sized according to the plant capacity, efficiency and varying flow rates between equipment within the process. The major parameters are given in Table **7**.

Table 7. Specifications for Sized Equipment

BLOW TANK	
Volume	3.54 m^3
Diameter	1.44 m
Height	2.16 m
Material of construction	Carbon steel
BLEACHING TOWER	
Volume	3.5 m^3
Diameter	1.14 m
Height	2.16 m
Material of construction	Stainless steel
STORAGE TANK	
Volume	11.4 m^3
Diameter	2.58 m
Height	3.87 m
Material of construction	Stainless steel

ENVIRONMENTAL IMPACT ASSESSMENT

The pulp and paper industry is governed by the following environmental legislations and laws; Environmental Management Act Chapter 20:27, Atmospheric Pollution Prevention Act Chapter 20:03, Zimbabwe National Water Authority Act Chapter 20:25, Hazardous Substances and Articles Act Chapter 15:05, Forestry Act Chapter 19:05, Water Act Chapter 20:22, Pneumoconiosis Act Chapter 15:08 and Factories and Works Act Chapter 14:08.

According to the environmental impact assessment (EIA), the potential impacts and their mitigation are indicated in Table 8.

Table 8. Summarized Impacts and Mitigation Measures for the Bagasse to Paper Plant

Stage	Negative impacts	Positive impacts	Mitigation measures
Construction	Noise and vibrations		Dampening instruments and ear protectors e.g. ear muffs to minimize vibration
	Destruction of natural ecosystem	Construction of access roads and service facilities	Vegetation replacement
	Land pollution		Erection of waste disposal bins on site and frequent litter picking
	Air pollution		Pre-treatment of effluent gases
Operation	Water pollution Air pollution	Continual development of the area	Minimize harmful emissions into water and air by thorough pre-treatment of effluent
Decommissioning	Inability to rehabilitate land Ghost sites creation Unemployment	Facilities can be used for other purposes such as training facility for locals	Train staff entrepreneurial skills

SITE SELECTION AND PLANT LAYOUT

Site Selection

Three possible sites were targeted and these were Harare, Mutare, and Chiredzi. The Chiredzi was chosen due to the following considerations indicated in Table 9.

Table 9. Description of Chiredzi Site

Factor	Description
Plant location	Near outskirts of sugar plantations
Availability of water	Municipal water, dams and/or boreholes, Save, Runde and Mkwasine river.
Population density	Semi-populated
Political stability	Stable
Availability of land	Plenty. The land is generally flat, well drained and has suitable load-bearing characteristics.
Local community considerations	Provision of hospitals, post offices, schools, police stations and other necessary facilities from which plant personnel can benefit.
Labor availability	Unskilled labour available
Market	Marketing area mainly Harare and Mutare.

Plant Layout

The principal factors that were considered in the optimum design of the plant layout were the process requirements, convenience of operation, economic considerations (construction and operation costs), and safety of workers and visitors to the site. The plant layout is shown in Fig. 9.

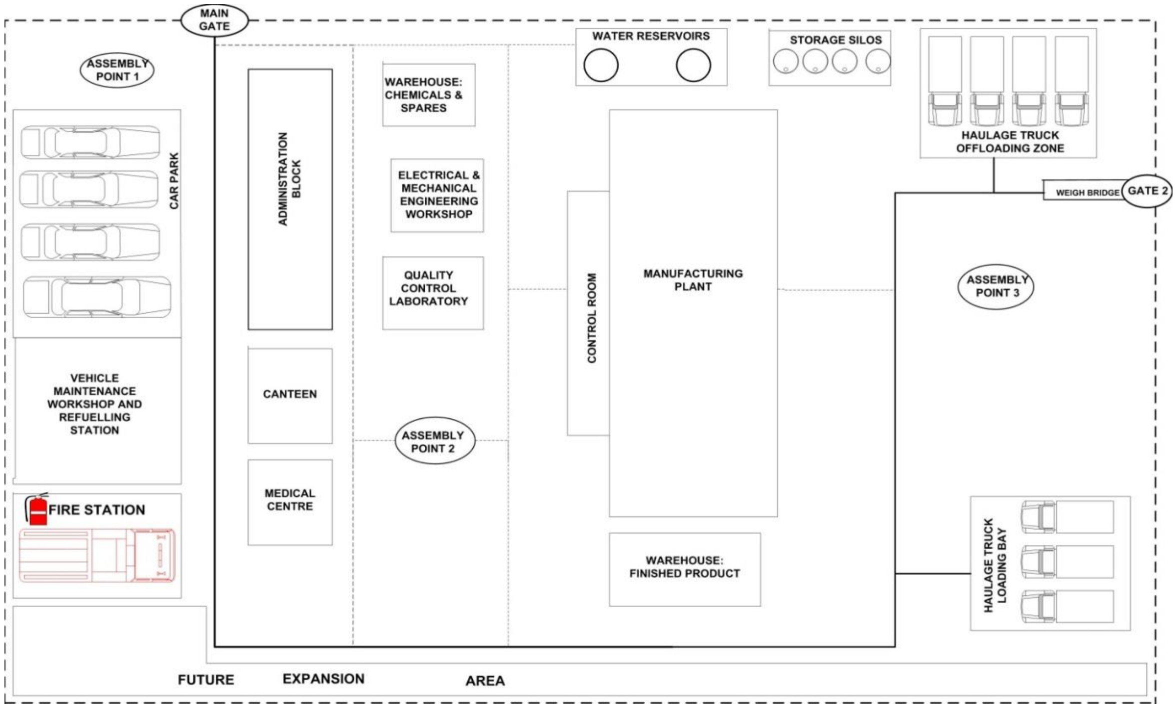

Fig. 9. Plant layout for bagasse virgin paper processing plant

ECONOMIC ANALYSIS

An economic analysis was carried out to assess the profitability of conversion of bagasse to paper in order to determine its commercial success. A commercially successful project is one that earns more or surpasses by a reasonable margin the capital costs incurred in establishing the project.

Capital Cost Calculation

Capital cost estimates for chemical process plants are often based on an estimate of the purchase cost of the major equipment items required for the process, the other costs being estimated as factors of the equipment cost (Sinnot 2006).

Purchased equipment cost

This factor represents a significant part of the investment cost, and these are given in Table 10.

Table 10. Purchased Equipment Cost

Equipment	Number of pieces	Unit cost ($)	Total cost ($)
Vibratory screens	1	6 000	6 000
Blow tank	1	11 000	11 000
Pulper	4	10 000	40 000
Blow tank	1	12 000	12 000
Bleaching tank	1	17 100	17 100
Rollers	10	1 000	10 000
Presses	3	1 400	4 200
Paper making machine	1	25 000	25 000
Conveyor dryer	1	26 000	26 000
TOTAL			151 300

Direct costs

These are added to indirect costs to determine the fixed capital investment. Table 11 summarises the direct costs.

Table 11. Direct Costs

Component	Range %	Selected	Amount $
Raw materials	(10~50) of production cost	20	46 237.28
Operating labour	(10~20) of production cost	15	34 677.96
Utilities	(10~20) of production cost	15	34 677.96
Maintenance and repairs	(2~10) of fixed capital	5	11 559.32
Operating supplies	(10~20) of maintenance	15	1 733.90
Lab charges	15 of labour	15	5 201.70
Patents and royalties	(0~6) production cost	5	11 559.32
TOTAL			145 647.44

Indirect costs

These are estimated on the basis of equipment cost (E). Percentages are obtained from Timmerhaus (1991). A summary of the indirect costs are given in Table 12.

Table 12. Indirect Costs

Item	Chosen %	Cost $
Engineering and Supervision	33 of E	49 929
Contingency	42 of E	63 546
Construction expenses	41 of E	62 033
Contractor's fee	21 of E	31 773
TOTAL		207 281

Fixed capital investment

Manufacturing fixed-capital investment represents the capital necessary for the installed process equipment with all auxiliaries that are needed for complete process operation.

FCI = $(207 281 + 145 647.44)
= $352 928. 44
≈ **$353 000**

Working capital investment, WCI = 20% of FCI

= 0.2 x $353 000

= $70 600

Total Capital Investment, TCI = FCI + WCI

= $(353 000 + 70 600)

= **$ 423 600**

Total production cost

This is the sum of the total manufacturing cost and total general expenses. Fixed costs are shown in Table 13.

Table 13. Fixed Costs

Component	Range %	Selected	Amount $
Fixed charges	(10~20) of FCI	11	38 830
Depreciation on machinery	10 of FCI	10	35 300
Depreciation on buildings	(2~3) of FCI	2	7 060
Local taxes	(1~4) of FCI	3	10 590
Insurance	(0,4~1) of FCI	1	3 530
TOTAL			95 310

The cost of plant utilities is given in Table 14.

Table 14. Power and Utilities Cost

Utility	Units / year	Cost / unit ($)	Total annual cost ($)
Steam	2 364.70	6.97	16 481.92
Electricity	395 566 kWh	0.15 / kWh	59 335
Water	260 000 m^3	2 / m^3	520 000
TOTAL			595 816

Maintenance and repair costs = 10% of FCI

= 0.1 x $353 000

= **$35 300**

Direct production cost = $(595 816 + 35 300 + 95 310)

= $726 426

Plant overhead cost **=** 10% of raw material cost

= 0.1 x $46 237.28

= **$4 624**

Total manufacturing cost, MC **=** Plant overheads + Production cost

= $4 624 + $ 726 426

= **$731 050**

General expenses for the plant are shown in Table 15.

Table 15. General Expenses

Item	Range %	Chosen %	Cost $
Administrative costs	2-6 of MC	2	14 621
Distribution and selling costs	12-20 of MC	12	87 726
Research and Development	5-7 of MC	5	36 553
Financing (interest)	0-10 of FCI	10	35 300
TOTAL			174 199

Total Production Cost, TPC =Manufacturing cost + General expenses

=$(731 050 + 174 199)

=**$905 249**

Profitability Analysis

Production capacity per year = 42TPD x 260 days

= **10 920 tons**

Production cost per unit $= \frac{Total\ production\ cost}{Total\ production}$

$= \frac{\$905\ 249}{10\ 920 tons}$

= $82.89 / ton

= **$83 / ton**

Adding a 30% mark up:

Selling price for virgin paper $= \frac{130}{100}$ x $83/ton

= **$108**

Total revenue =10 920 ton/ year × $108 /ton

=$1 179 360

Gross profit = Total revenue – Total production cost

= $1 179 360 - $905 249

= **$274 111**

Tax paid = 0.3 x Gross profit

= 0.3 x $274 111

= **$82 233**

Net profit = Gross profit – Tax paid

= $274 111 - $82 233

= **$191 878**

Return on investment and payback period

ROI $= \frac{191\ 878}{423\ 600}$ x 100%

= **45 %**

PB $= \frac{100}{45} \text{ x 1 yr}$

$= \mathbf{2.2\ years}$

Net Present Value

A plant lifespan of 10 years was assumed considering the technological advancement and the net present value is indicated in Table 16.

Table 16. Net Present Value Determination

Year	Net Cash Flow ($)	Discounting factor	Present value ($)
0	-423,600.00	1	-423,600
1	191,878	0.909	174,417
2	191,878	0.826	158,491
3	191,878	0.751	144,100
4	191,878	0.683	131,053
5	191,878	0.641	122,994
6	191,878	0.564	108,219
7	191,878	0.513	98,433
8	191,878	0.466	89,415
9	191,878	0.424	81,356
10	191,878	0.38	72,914
Total			**1,181,393**
Net present value			**757,792.85**

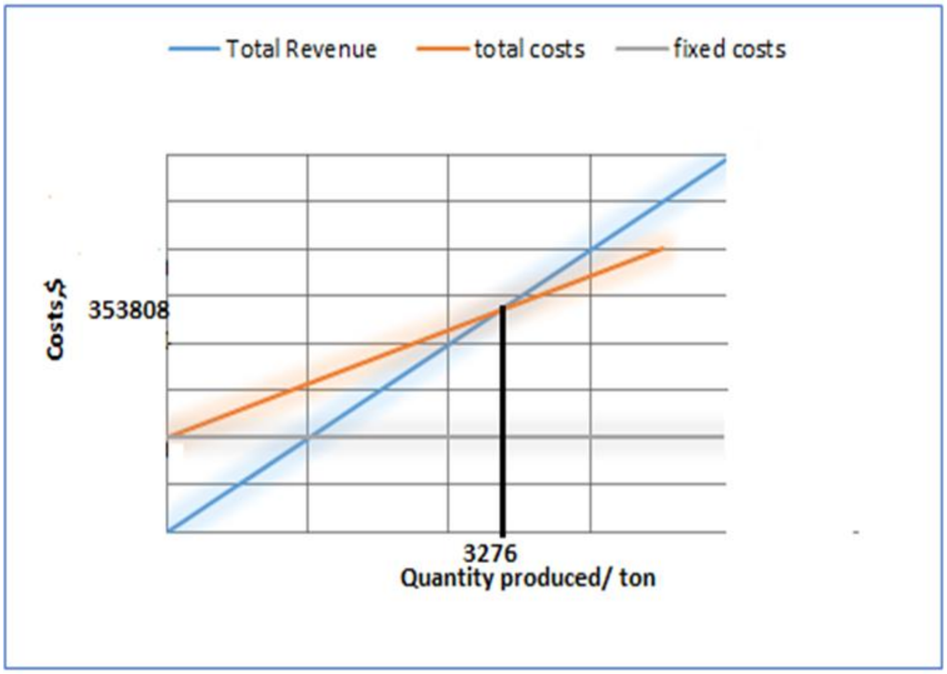

Fig. 10. Break even chart

Break Even Analysis

Number of units needed to break-even point $= \frac{30}{100}$ x 10 920 tons

= **3 276 tons**

Break even in monetary terms = 3 276 tons x $108 / ton

= $353 808

The break even chart is shown in Fig. 10.

CONCLUSIONS

1. Production of virgin paper from bagasse is technically and economically feasible using the kraft pulping process with a pulping yield of 35%.
2. An environmental impact assessment demonstrated that very minimal environmental damage will be caused by the establishment of the proposed bagasse-to-virgin paper processing plant.
3. A financial analysis of the project indicated the economic viability of this technology with a payback period of 3.33 years and a return on investment of 30%, with the virgin paper selling at $108.00/ton.

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