REFEREED PAPER

S-BEAT: A PRELIMINARY COST ESTIMATION METHOD FOR THE SUGARCANE BIOREFINERY

NAIDOO P[1,2], LOKHAT D[1] AND STARK A[1]

[1]*University of KwaZulu-Natal, Discipline of Chemical Engineering, King George V Avenue, Durban, 4041, South Africa*
[2]*Sugar Milling Research Institute NPC, c/o University of KwaZulu-Natal, Howard College Campus, Durban, 4041, South Africa*

pnaidoo@smri.org lokhat@ukzn.ac.za starka@ukzn.ac.za

Abstract

In recent years, key stakeholders within the South African sugar industry have been assessing the potential to further diversify their product portfolios. The suggested route is to assess the available sugar mill streams for their potential to manufacture value-added products. In principle, a multitude of new revenue streams can be generated which will serve markets of different sizes and values. As a first stage assessment to allow for the selection of the most economically attractive product or process candidates, the Sugar Milling Research Institute NPC had developed the New Product Greenhouse (NPG) toolbox, by which the vast number of options is reduced by assessing easily accessible parameters, such as stoichiometry, capacities and market sizes. In this paper, as a second stage, the advanced Sugarcane Biorefinery Economic Analysis Toolbox (S-BEAT) is introduced, providing both a cost estimation and economic analysis at a preliminary process design stage for preselected alternatives.

Targeting processes with high technology readiness levels, the order of magnitude approach is used, which is based on data of existing plants. It accepts historical data and escalates the capital investment to the current year, whilst making adjustments for differing product capacities and plant locations. It is estimated that this method has an accuracy of about ±30% to ±50%, which is considered satisfactory for a preliminary cost estimate. The cost estimates then undergo an economic analysis to determine product profitability, and allow for comparison between process and product alternatives.

In order to demonstrate the potential of S-BEAT, the production of high-density polyethylene (HDPE) and polylactic acid (PLA) from clear juice was investigated. The resulting economic analysis highlights the commercial attractiveness of the products as assessed by the tool.

Keywords: sugarcane juice, cost estimation, economic analysis, feasibility, methodology, preliminary

Introduction

The emergence of bio-based products and chemicals as alternatives to those derived from fossil resources is of great importance in an age noted for its increasing crude oil prices, global pollution and waste management problems (Tran *et al*., 2004). Bio-based products made from agricultural materials are renewable and hence reduce the reliance on fossil resources. Additionally, they are often non-toxic and less harmful to the environment. Most importantly, the local manufacture of these products extends beyond environmental sustainability as they have the potential for economic benefits. Starting with a reduced dependence on fossil resources, and a general upliftment of the agricultural sector, potential reductions in the capital and operating costs, process steps and energy consumption may be expected, and wastes generated can be safely removed or upcycled.

A sugarcane-based biorefinery for the production of renewable chemicals has the potential to become a prosperous endeavour for the following reasons (Nel, 2009): The infrastructure, labour force and utilities of an existing mill can be used with some modifications or expansions. For example, the juice extracted from the cane can be fermented to become a feedstock for a wide range of renewable chemicals. The bagasse generated, which is currently used as a boiler fuel, can become a feedstock for numerous chemicals as well, provided that a surplus of bagasse is available.

The extensive product portfolio that sugarcane could generate requires an in-depth analysis prior to any rigorous design for a biorefinery. The New Product Greenhouse (NPG) toolbox, developed by the Sugar Milling Research Institute NPC (SMRI), provided the first step in this pursuit for sustainability. The toolbox is a screening tool, which uses built-in algorithms to rank the commercial feasibility of new products (Booysen *et al*., 2017). However, the absence of capital and operational expenditure (CAPEX and OPEX) estimates implies that further assessment of the products is necessary before an informed decision can be made. Hence, as a second assessment stage, the Sugarcane Biorefinery Economic Analysis Toolbox (S-BEAT) was developed, which aims to provide a CAPEX, OPEX and economic assessment of those products passing the NPG assessment stage.

Development of S-BEAT

A rigorous and detailed chemical engineering design is often a prerequisite to obtaining plausible CAPEX and OPEX estimations, a task that is usually daunting, time-consuming and costly to perform for each potential product and process alternative. The intensity of this task tends to multiply when a comparison of the economic feasibility for a multitude of products is required. When faced with this dilemma, the following questions arise:

- Is it possible to obtain a reasonable first cost estimate without spending a great amount of time and/or resources?
- Can a generic methodology result from this?
- Will the methodology allow for the comparison of both different process alternatives and different products?
- Which economic indicators can be used to allow for this comparison?

By taking the above into consideration, a preliminary cost estimation methodology was developed, making use of a user-friendly Microsoft Excel workbook. The method was generalized for the comparison of a variety of potential processes and products that could arise from sugarcane.

S-BEAT employs the order-of-magnitude (OOM) method, which accepts historical data of an existing plant or valid literature, in response to the time and resource constraints. The OOM method escalates the historical data to account for the passage of time and/or major plant geographical changes. Adjustments are also made for differing plant capacities. With an estimated accuracy of greater than ±30% (Sinnot, 2005) to ±50% (Brown, 2006), the resultant cost can be regarded as a preliminary estimate. It must be noted that the accuracy is dependent on site and scenario specific situations. Products or process alternatives that have passed this second assessment stage would only then undergo rigorous design, including detailed material and energy balances, thorough equipment design and plant optimizations.

S-BEAT is comprised of five main sections, viz. Data collection, CAPEX, OPEX, Economic Analysis and Economic Results, arranged on different sheets within an integrated Excel workbook. Excel's easy to use interface allows the user to input the requested requirements, before the calculations are executed and the results presented in an intuitive manner. The methodology and assumptions employed by S-BEAT are presented in the subsequent sections.

Data Collection

Reference (historical) plant data requirements

The OOM approach requires the capital investment, product capacity, plant year of construction and location of a historical or existing plant. S-BEAT requests these parameters from the user. Many literature sources can be consulted with varying degrees of accuracy attached to each. The information obtained directly from a company's cost database, of their historical projects, would have a higher accuracy (Dysert, 2003) than that obtained from a (often rather vague) press release. On the other hand, a literature design may provide a relatively accurate plant design cost; however, the plant location or year of the design may be unspecified. Several additional factors that affect the accuracy of the capital investment should be considered. These factors often become constrained by the limitations of readily available information. Nevertheless, the raw material feedstock and an idea of the process equipment remains a necessity, because a differing feedstock base requires different processing technologies which have a great impact on the capital investment. Furthermore, the reference plant year should be less than 10 years (Peters and Timmerhaus, 1991) in the past relative to the design year for the intended plant.

Intended (new) plant data input

At this stage of the development of S-BEAT, processes using sugarcane juice as the raw material feedstock can be assessed, and future extensions will be incorporated to allow for the selection and comparison of further streams. The default flowrate and composition of the juice were obtained from the South African Generic Sugar Mill Model developed by Kylan Guest[1]. The user may opt to use the default values or to input their own. Furthermore, a percentage of the juice stream can be diverted to downstream operations whilst the remainder is used for sugar production. Currently, S-BEAT does not consider the effects that this diversion will have on the manufacture and economics of the sugar process; however, the loss in potential sugar revenue will be addressed in future work.

Detailed mass and energy balances are unavailable at this preliminary stage for alternative product assessments. S-BEAT performs a simple stoichiometric calculation, using the flowrate and composition of the specified feedstock, to obtain the intended plant's production capacity. For this purpose, the user is requested to input the main chemical reactions associated with the process as well as well-known overall reactor conversions and separation purities.

The design location is pre-defined as South Africa and the design year can easily be adjusted. The design year should ideally be the 'current' year (i.e. relative to the toolbox evaluation). S-BEAT assumes that the time-dependent data are up to date to the time of the intended plant design. In reality, the data are updated to the most recently accessible information. For example, if the intended plant is for South Africa in 2018 and the reference data is for a Brazilian plant, it is assumed that S-BEAT has the 2018 location factors. Realistically, the location factors in S-BEAT could be valid for 2016 only. The sugarcane season, operational hours and shifts per day are set to the default values of 252 days, 24 hours and three shifts, respectively, and these values can be easily adjusted.

[1] Personal communication, K. Guest 2017 (MSc thesis, Development and Verification of an Aspen Plus® Model of a Sugarcane Biorefinery, UKZN).

Capital Expenditure

The information requested and calculated in *Data Collection* is transferred to the *CAPEX* section, where the capital investment required for the product of interest is evaluated. The capital cost of a project is a once-off expenditure that generally occurs at the beginning of the project. It includes direct and indirect costs.

The direct costs are those required to construct the plant and comprise the purchase and installation of equipment, piping, instrumentation, process and ancillary buildings, storage, utilities and site preparation. The indirect costs cover the cost of design and engineering, contractor's fees and contingencies for unforeseen circumstances (Sinnot, 2005). These costs comprise the Fixed Capital Investment (FCI). Approximately 10% of the FCI is defined as the Working Capital (WC) of the project. The WC is allocated to the start-up operations of the plant, which are required to operate the plant until the process generates an income.

The sum of the Fixed and Working Capital results in Total Capital Investment (TCI). S-BEAT requests the FCI or TCI from the user, as this is often accessible information. As mentioned above, these historical costs require capacity, time and location adjustments before they can be used as the capital investment of the intended plant. The FCI is then described by Equation 1.

$$FCI_{New}^{*} = FCI_{Ref} \times \left(\frac{Capacity_{New}}{Capacity_{Ref}}\right)^{n} \times \left(\frac{CEPCI_{New}}{CEPCI_{Ref}}\right) \times \left(\frac{Location\ Index_{New}}{Location\ Index_{Ref}}\right) \tag{1}$$

where CEPCI is the Chemical Engineering Plant Cost Index.

Capacity adjustments

A capacity adjustment is required when the reference and proposed plants have different production capacities. The cost capacity factor *n* accounts for the nonlinear relationship that exists for facilities with similar technologies but different capacities. A factor less than one is indicative of economies of scale; it is extensively reported in literature for a variety of equipment, products and processes.

S-BEAT uses the factors reported by Remer and Chai (1993) in Encyclopedia of Chemical Processing and Design. Several hundred cost capacity factors for various products and their process routes are tabulated. If a specific product is unavailable, average factors exist for different process industries; gases, polymers, biotechnology etc. (Remer and Chai, 1993). S-BEAT allows the user to select from these exponents based on their product of interest and the process route it takes. If this option is inadequate, an average value of 0.67 can be used.

Time adjustments

An existing plant is often constructed in a year prior to the proposed plant. Adjustments are required to account for the inflationary changes, which occur between these years. The CEPCI is used for this purpose. This composite index, which was developed for the United States process industry, comprises of equipment, construction labour, buildings and engineering and supervision (Towler and Sinnott, 2012).

The index is published monthly in Chemical Engineering (Chemical Engineering, 2017); however, a time-delay exists in obtaining the final monthly/annual values. S-BEAT selects the index based on the supplied historical and proposed years. The tool uses the most recently available and not the exact index, which introduces a level of inaccuracy to the calculation. However, the default values can be changed if a user has access to the current index values.

Location adjustments

Location adjustments must be made when an existing plant has been constructed in a different location to the proposed plant. The location factor considers the differences in engineered equipment, productivity and labour costs, commodities, duties, freight, taxes, procurement etc. (AACE International, 2006).

S-BEAT's current default location factor uses the Deloitte Global Manufacturing Competitiveness Index (Deloitte Touche Tohmatsu Limited, 2016[a]), since the more accurate Richardson Location Factors (Richardson Engineering Services, 1996) are not freely accessible. For this purpose, Deloitte conducts surveys to understand how the manufacturers assessed their processes' competitiveness. The survey comprises three sections, i.e. business confidence and current economic outlook, manufacturing competitiveness, and demographics (Deloitte Touche Tohmatsu Limited, 2016[a]).

S-BEAT allows the index to be adjusted to accommodate company-internal location factor preferences. It should be noted that greater accuracy would ensue when the source of the location factor is the same for product comparison purposes.

Contingency adjustment

An additional contingency adjustment is allocated to the FCI, to be modified at the user's discretion. The factor should account for any reservations with the cost capacity factor, CEPCI, location factor or any other parameters. The default value is set to 5% of the FCI, the WC and TCI are then calculated with Equation 2, 3 and 4, respectively:

$$FCI_{New} = FCI^{*}_{New} + 0.05FCI^{*}_{New} \tag{2}$$

$$WC = 0.1FCI_{New} \tag{3}$$

$$TCI = FCI_{New} + WC \tag{4}$$

Operational Expenditure

OPEX is an ongoing estimation that evaluates the costs associated with product manufacturing. It consists of Variable Production Costs (VPC), Fixed Production Costs (FPC) and General Expenses (GE). Their summation results in the Total Production Costs (TPC). VPC are those that depend on the quantity of the product produced, and include raw material costs, utilities and miscellaneous materials (Sinnot, 2005). Additionally, a waste management factor is included in the VPC to account for the disposal of effluent streams. This factor can be adjusted to suit the scenario in question, as certain product effluents require more extensive treatment.

FPC are independent of the product quantity and are comprised of operating labour, supervision, laboratory costs, plant overheads, maintenance, capital charges and insurances (Sinnot, 2005). The GE include research and development, sales expense and general overheads, for completeness of the operational expenses. The OPEX is calculated by applying factors to the FCI, calculated operating labour, maintenance or the TPC (Table 1). The iterative nature of the calculation is handled with ease in Excel.

Table 1. Procedure to calculate the Total Production Costs for the product of interest.

Item	Factor	Basis
Variable Production Costs		
Raw Materials	-	See *Raw Materials*
Miscellaneous Materials	10%	of Maintenance[a]
Utilities	15%	of TPC[b]. See *Utilities*
Waste Management	5%	of TPC
Fixed Production Costs		
Maintenance	5%	of FCI[a]
Capital Charges	10%	
Insurance	1%	
Local Tax	2%	
Operating Labour	-	See *Operating Labour and Salaries*
Salaries	-	See *Operating Labour and Salaries*
Laboratory Costs	20%	of Operating Labour[a]
Supervision	20%	
Plant Overheads	50%	
General Expense		
Sales Expense	2%	of TPC[b]
General Overheads	2%	
Research and Development	2%	
Total Production Costs (VPC + FPC + GE)		

[a] (Sinnot, 2005), [b] (Peters and Timmerhaus, 1991)

Raw materials

It is assumed that the sugarcane juice cost is a major contributor of the raw materials as such, and is the only material accounted for. The juice cost is estimated according to a method proposed by Chikava (2018), making use of the Recoverable Value (RV) of cane[2] whilst adjusting for the operational costs associated with obtaining clear juice. The operations factor is a percentage of the proceeds allocated to the miller, the value of which is added to the cane RV cost (Chikava, 2018). The procedure, with the 2015/2016 cane cost, is outlined in Table 2. The method employed is purely for research purposes and the operations factor will be adjusted once accurate cost distributions over a mill have been obtained. S-BEAT allows for its default values or company internal costs to be used.

Table 2. Method used to calculate the cost of sugarcane juice, with values based on 2015/2016 cane cost.

Cane Juice Cost	Value
Cane Cost RV (R / t RV)[2]	3 979.22
Cost to Miller (R/ t RV)	2 202.81
Operations Factor	25%
Operations Cost (R)	550.70
Juice Cost RV (R / t RV)	4 529.92
RV% Juice (%)	11.09

[2]Research – SA CaneGrowers, https://sacanegrowers.co.za/research/, last accessed on 10 March 2018

Utilities

The cost of utilities, i.e. electricity, steam and water, are taken as a percentage of the Total Production Cost. When a full material balance of the mill becomes available through future studies, the utilities will be priced on their material flow rates and the cost in South Africa. At present, 15% of the Total Production Cost (Peters and Timmerhaus, 1991) is used. However, this can be easily adjusted to suit the specific scenario.

Operating labour and salaries

The operating labour is estimated on the number of operators required per process equipment (Brown and Brown, 2014). A brief process description, which outlines the major equipment, is therefore required for each product of interest. For equipment that is not available, a value of 0.1 operators required per process equipment was assumed. A summation of the operators required for the process multiplied by an equipment operators' salary[3] result in the operating labour.

The salaries of a plant manager, process engineer, admin clerk and secretary[4] were obtained for completeness. It is assumed that supervision incorporates the salary for maintenance and shift supervisors and is therefore not included in salaries.

Other expenses

The consumables, catalysts, solvents and enzymes have an initial start-up cost which is accounted for in the Working Capital. This is at present an underestimation as material flow rates are not available; however, it is deemed suitable for this preliminary estimation.

Economics

An engineer affects a company's ability to turn a profit in a variety of ways, from creating new products/processes to modifying existing products/processes intending to reduce costs and/or improving efficiencies (Brown, 2006). Before a decision is made on whether to extend an existing plant, e.g. to include a biorefinery unit downstream of an existing sugar mill, the engineering team must investigate which products and processing routes are economically viable. The economic indicators, which are used to assess the viability of a project, are the Net Present Value (NPV), Internal Rate of Return (IRR) and Payback Period (PBP). These indicators are evaluated on completion of a Discounted Cash Flow (DCF) analysis.

Discounted cash flow

The results from *CAPEX* and *OPEX* are utilised in the Discounted Cash Flow (DCF) analysis. A Cash Flow analysis identifies and categorises a project's inflow and outflow of cash. The DCF is an extension to the Cash Flow analysis that takes the time value of money into account (Peters and Timmerhaus, 1991). The time value of money, simply put, states that the present value of money is higher than its future value. For a defined project lifetime, the future cash flow is projected and then discounted to its present-day value.

The Capital Investment, annual Total Production Costs, annual sales, depreciation and taxation are included in the DCF to obtain the annual Cash Flow. An escalation rate is applied to the product Selling Price and the VPC to account for inflationary effects. S-BEAT uses the

[3]Payscale.com, https://www.payscale.com/research/ZA/Job=Chemical_Process_Operator/Salary, last accessed on 11 May 2017
[4]Payscale.com, https://www.payscale.com/research/ZA/Job=Secretary/Salary/b8f835d5/Durban, last accessed on 11 May 2017

Modified Accelerated Cost Recovery System (MACRS) to account for depreciation tax. MACRS is the preferred method when the size of the asset under consideration is large. For engineering equipment in a chemical engineering plant, the MACRS for South Africa is over a four-year period of 40% in year one and 20% for each subsequent year (Deloitte Touche Tohmatsu Limited, 2016[b]).

A discount rate is applied to the total annual Cash Flow to obtain its present value. The discount rate used can be pre-defined as a company's Minimum Acceptable Rate of Return (MARR) (Brown, 2006). The MARR is the minimum return that a company finds acceptable before undertaking a project.

Economic indicators

The NPV is the total of the annual discounted cash flows over the project's life. A positive NPV is indicative of an economically favourable project and it demonstrates that the project can generate a profit whilst bearing the cost of capital. The time taken to recover the initial investment of a project is termed the Payback Period (PBP), which ideally should be as short as possible to free up capital for new investments. The Discounted PBP is the period taken for the cumulative discounted cash flows to reflect a positive value. It is the year, in the project lifetime, that has an NPV of zero.

The IRR is the rate of return that results in a NPV of zero. A project should be accepted if the IRR is greater than the MARR. Simplistically, if it costs 10% to borrow money, then the IRR should be greater than 10% to prove worthwhile. When comparing projects, the project with a higher IRR is economically more attractive. Nevertheless, care must be taken when ranking a project according to its IRR alone. The IRR is a relative measure and it isn't affected by a project's size, whilst the NPV is an absolute measure. Hence, the NPV bears the higher informative value and should be considered first when ranking a project. The FCI should be consulted together with the NPV, as many smaller projects with a lower NPV could potentially be more beneficial than one large project with a high capital investment and NPV.

Sensitivity analysis

Various components in S-BEAT contribute to the overall uncertainty of the economic results. Potential inaccuracies are:

- The literature reference source.
- The OOM method.
- Source of the location factors.
- Reference year: leading to incorrect CEPCI values and exchange rates.
- Availability of time-dependent values.
- The raw material costing procedure.
- The product selling price.
- The factors utilised to calculate OPEX.

A sensitivity analysis can quantify these inaccuracies, by investigating deviations from the expected results due to changes in the input parameters. The expected results are the economic parameters, whilst the input parameters are generally those listed above. Which parameter is assessed in the sensitivity analysis often depends on company internal intelligence, and can be freely chosen in S-BEAT. By examining the extent of the variations, one can rank the potential inhibitors and concentrate on improving their accuracy.

Case Studies

Two case studies were investigated to present the methodology implemented in S-BEAT, viz:

1. Sugarcane Juice → Ethanol → Ethylene → High Density Polyethylene (HDPE)
2. Sugarcane Juice → Lactic Acid (LA) → Lactide → Polylactic Acid (PLA)

Thomson (2017) extensively investigated the SA market potential for bio-based HDPE and PLA. HDPE is used to produce packaging, bottles, piping and other plastic materials. The most important characteristic of bio-HDPE is that it is a 'drop-in' substitute for petroleum derived HDPE. This implies that bio-HDPE does not face technological hindrances in the downstream processes, if it were to be pursued. PLA on the other hand is a new, biodegradable polymer, which is mainly used for the production of packaging items. PLA would experience greater difficulties in production, as it is not a 'drop-in' but a competitor substitute and would require adjusted processing technologies (Thomson, 2017). Thomson (2017) concluded that the SA market would accept HDPE and PLA; however, the demand for PLA is currently not yet high.

Case study basis

The basis of the case studies was that the biorefinery additions would be integrated into a South African sugar mill. The design year was taken as the year ending 2016, as complete data were available. The feed flowrate was specified as 50% of the clear juice stream, which was diverted to the respective biorefinery operation, while the remaining clear juice would be used to make sugar. At this stage of S-BEAT development, it was assumed that the steam, electricity and water utilities generated by the sugar mill would be sufficient to run the downstream biorefinery additions. The default operational days, hours and shifts were selected. Since the majority of the literature was available in US dollars, an exchange rate was required to relate it to the South African market. The average exchange rate of 2016 was used for this purpose.

Table 3. CAPEX parameters which are common to both case studies.

Parameters	Value
Design Location	South Africa
Design Location Factor	48.10[c]
Design Year	2016
Design Year CEPCI	541.70[d]
USD/ZAR Design Year (R)[5]	14.57
Operating Days	252
Clear juice capacity (t/h)	140.84

[c] (Deloitte Touche Tohmatsu Limited, 2016a) [d] (Chemical Engineering, 2017)

Literature data

Literature was consulted to get data for the reference plant. If possible, it would have been preferable to use information for plants that had the installed equipment for cane juice directly to HDPE or PLA. Instead, plant information was obtained for each separate product, which had the previous product as its feed material. The data are presented in Table 4.

[5] Investing.com, https://za.investing.com/currencies/usd-zar-historical-data, last accessed on 11 May 2017

Table 4. Literature information used as the historical reference data in the calculations and for the new product capacity calculations.

Parameters	Ethanol[e]	Ethylene[6]	HDPE[g]	LA[h]	Lactide-PLA[k]
Reference / Company	Virtual Biorefinery	Intratec	LyondellBasell	Purac	Intratec
Capacity (t/ann × 10^3)	84.00	300.00	320.00	120.00	100.00
Capital Investment (USD × 10^3)	32 840.83	260 000.00	278 677.05	130 177.98	100 000.00
Location	Brazil	USGC	Germany	Thailand	USGC
Year	2014	2014	2009	2007	2015
Overall Conversion (%)	90.00[f]	99.00	100.00	90.00[i]	94.00-95.00
Overall Purity (%)	99.70[f]	99.90	-	98.00[j]	99.70

[e] (Bonomi *et al*., 2016), [f] (Dias, 2010), [g] (Maire Tecnimont, 2008), [h] (Kramer, 2013), [i] (Purac Biochem BV, 2003), [j] (Timbuntam *et al*., 2006), [k] (Jenkins, 2015)

The ethanol plant data was obtained from the Virtual Biorefinery, which is dedicated to the Brazilian sugarcane industry. The plant capital investment and capacity were used for the case study of an ethanol distillery annexed to a sugar mill. A breakdown of the investment was available and the costs associated with the sugar mill were deducted. Thus, the FCI used was for an ethanol distillery with cane juice as its feed stream. The year and location were explicitly stated. The reactor conversion, separation purity and equipment list were obtained from a supplemental document (Dias, 2010). It is important to note that modifications to the reference plant can be made, if possible, so that the reference plant and the new plant are similar. For ethanol it was possible as the cost breakdown was explicitly stated and hence the mill costs could be removed.

The Intratec Chemical Process Library is a freely available source of data detailing manufacturing technology descriptions and the economics associated with them. It was used as a reference for several processes.

For ethylene production, using Intratec as the reference, the process selected was like that of Chematur Technologies AB and Petron Scientech Inc. for dehydration of ethanol to ethylene (Intratec Solutions, 2017). The location, economic year, major equipment list, overall conversion and product purity are explicitly indicated. The resulting polymer-grade ethylene is the feed to the HDPE process.

The HDPE reference data were obtained for the engineering design, supply and construction of a HDPE facility in Münchsmünster, Germany (Maire Tecnimont, 2008). The contract value was stated for the period nearing the end of construction; as such, it was used as the reference year. The technology employed in the plant is the LyondellBasell Hostalen ACP process technology. The process stages were stated, in the technology brochure, as catalyst feeding, polymerisation, powder drying, extruder and pellet handling and recycling[7] (LyondellBasell Industries Holdings BV, 2017). A simplified process scheme was then obtained from Daftaribesheli (2009).

[6]Ethylene Manufacturing Technology Description, https://www.intratec.us/free-tools/how-to-make/ethylene-manufacture-technology, last accessed on 11 August 2017
[7]LyondellBasell Polyethylene Technologies, https://www.lyondellbasell.com/globalassets/products-technology/ technology/hostalen-brochure.pdf, last accessed on 17 August 2017

The LA reference plant information was for the Purac (now Corbion) Thailand plant. The data were obtained from various Corbion related sources. Intratec's[8] process description was adopted whereby a similar process to the Purac plant was described and glucose was the feed material. The capital investment stated was assumed to be the FCI and the plant year was available. The PLA production process described by Intratec was used, whereby LA is converted to lactide and then polymerized to PLA. However, the design year was not explicitly stated so the article year was used for this purpose (Jenkins, 2015).

The LA process description and process flow diagram (Figure 1), adapted from Intratec Solutions[8] (2017), are further described below.

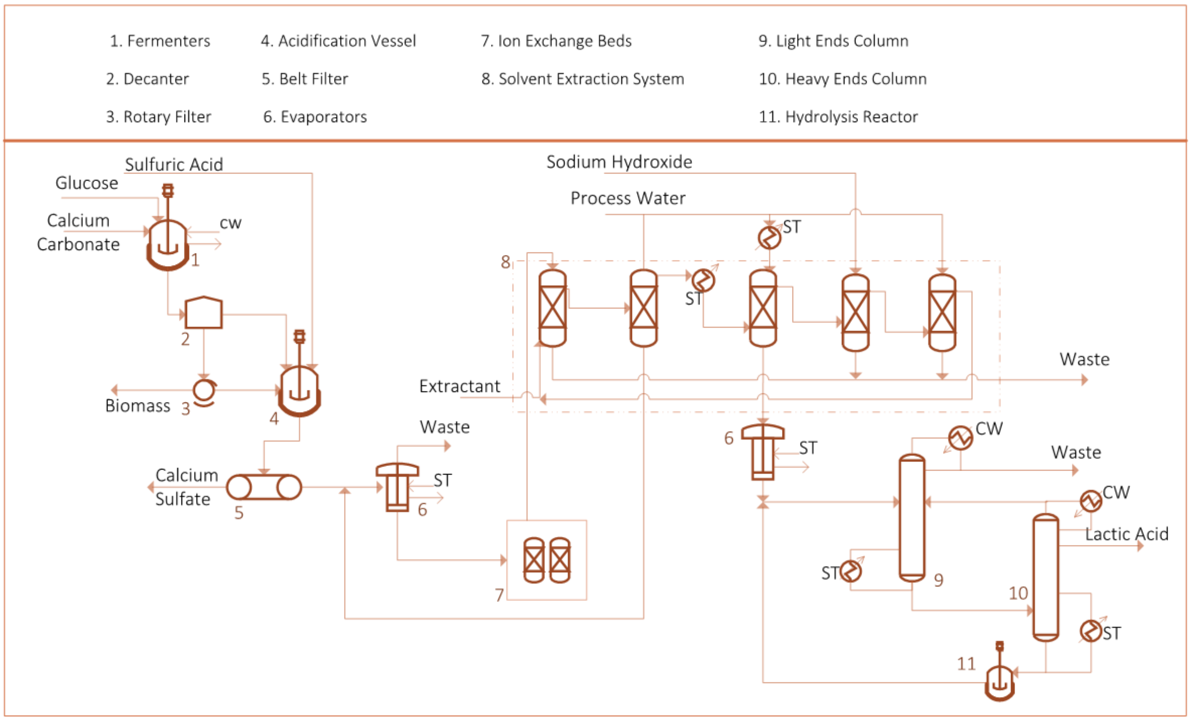

Figure 1. Lactic Acid process flow diagram adapted from Intratec Solutions (2017)[8].

LA is produced by feeding a glucose stream into a continuous anaerobic bacterial fermenter. The fermentation temperature and pH are controlled through reactor-internal coils, which circulate cooling water and dose $CaCO_3$. The $CaCO_3$ reacts with the lactic acid to form calcium lactate. The lactic acid is recovered through decanting the fermentation broth and filtering the concentrated solids. Sulfuric acid is then added to the aqueous suspension that resulted from the decanter and rotary filtration. The calcium lactate is converted into soluble lactic acid and a precipitate of $CaCO_3$. The $CaCO_3$ is removed via a belt filter, the resulting filtrate is then sent to an evaporator where it is concentrated. The evaporator outlet stream is then purified in ion-exchange columns. The stream, which leaves the ion-exchange columns, enters a 5-stage solvent-extraction system. Process water and an aqueous solvent is used in the extraction system to remove any contaminants. The LA-rich aqueous solution which leaves the system enters a second evaporator. A 2-column distillation system follows the evaporator. The waste stream is removed from the light ends of column 1, whilst the heavy ends are sent to column 2. A side stream of LA is recovered from column 2; this is the main product. The light ends are recycled to column 1 and the heavy ends are hydrolysed in a reactor. The hydrolysed reactor outlet is then recycled to column 1 in the distillation sequence.

[8]Lactic Acid Manufacture Technology Description, https://www.intratec.us/free-tools/how-to-make/lactic-acid-manufacture-technology, last accessed on 17 August 2017

S-BEAT application: Results and Discussion

CAPEX

The calculation parameters and the resultant FCI for each product are shown in Table 5. The cane juice flowrate (Table 3), overall conversions and purities (Table 4) were used to estimate the product capacities. The capacity exponents were then selected as follows (Remer and Chai, 1993):

- Fermentation of sugarcane to obtain ethanol has an exponent of 0.90.
- Ethylene (at a capacity between 20 000 - 200 000 t/annum), has an exponent of 0.83.
- Polyethylene produced from ethylene has an exponent of 0.65.
- Since LA from fermentation and PLA from LA are not listed, the average exponent of 0.67 was used.

Table 5. CAPEX calculation procedure and results.

Parameters	Ethanol	Ethylene	HDPE	LA	Lactide-PLA
Capacity (t/ann × 10^3)	48.67	29.32	29.32	93.55	66.63
Capacity Exponent[l]	0.90	0.83	0.65	0.67	0.67
CEPCI[m]	576.10	576.10	521.9	525.4	556.8
Location Factor[n]	46.2	99.5	93.9	60.4	99.5
FCI (R × 10^6)	300.97	262.33	479.33	1 383.87	548.13

[l] (Remer and Chai, 1993), [m] (Chemical Engineering, 2017), [n] (Deloitte Touche Tohmatsu Limited, 2016a)

Thomson (2017) presented approximations of 240 000 and 55 000 tonnes of imported and exported PE, respectively, as 2015 SA figures. From Table 5 it can be seen that only 29 320 tonnes of HDPE is produced using 50% of the mill's clear juice stream, hence the amount of HDPE produced could complement the market without flooding it. On the other hand, Thomson (2017) stated that it is difficult to estimate the demand for PLA in SA, as it is currently not produced or converted. He further suggested that 50 000 tonnes per annum would be enough for internal and domestic markets. Table 5 shows that 50% of the clear juice stream would result in a PLA capacity of 66 630 tonnes per annum, indicating that this capacity would initially be sufficient.

OPEX

The calculation method used to obtain the operating labour requires the major equipment for the case study of choice. The LA acid process is used to demonstrate this method. The major equipment list can be inferred from Figure 1. Since the feed material from the reference source is glucose instead of a sucrose juice stream, a hydrolysis reactor is added to convert the sucrose to glucose and fructose. In this current assessment, it is assumed that additional equipment costs will be accounted for by the contingency factor in the FCI calculation (Table 6).

If 3.43 operators/shift are required then 11 (10.29) operators are required for three shifts. For a salary/operator/season of R131 633[4] (PayScale, Inc., 2017), the annual operating labour for LA production is R1 448 000. Utilising the OPEX factors in Table 1, the output production cost data is calculated and tabulated in Table 7.

Table 6. Example of the operating labour calculation procedure for lactic acid (LA).

Major equipment[8]	Operators/unit[o]	Number of units	Operators/shift
Reactors	0.25	3.00	0.75
Decanter	0.10	1.00	0.10
Acidification vessel (mixer)	0.13	1.00	0.13
Rotary filter	0.05	1.00	0.05
Belt filter	0.05	1.00	0.05
Ion exchange beds	0.10	2.00	0.20
Solvent extraction system	0.25	5.00	1.25
Evaporator	0.15	2.00	0.30
Columns	0.25	2.00	0.50
Heat exchangers	0.05	2.00	0.10
Total		20	3.43

[o] (Brown and Brown, 2014)

Table 7. OPEX Results.

Parameters	Ethanol	Ethylene	HDPE	LA	Lactide-PLA
Juice Cost (R × 10^6/a)	427.90	-	-	427.90	-
Operating Labour (R × 10^3 /a)	789.78	1 184.69	921.43	131.63	1 447.96
VPC (R × 10^6 /a)	560.76	15.04	26.84	620.66	30.89
FPC (R × 10^6 /a)	56.60	49.47	88.03	252.77	101.41
TPC (R × 10^6 /a)	656.76	68.63	122.20	929.18	140.75

Economic analysis

The plant lifetime was pre-defined as 20 years for each potential process. Arbitrary percentages of 3.5% and 1.0% increase were assumed for the selling price and TPC inflations, respectively. The Modified Accelerated Cost Recovery System (MACRS) was used to show depreciation of the capital assets in the plant. The DCF economic parameters and economic results are shown in Tables 8 and 9, respectively. Industry representatives[9] stated the MARR as 23% in 2016, however, it was noted that that was quite a high hurdle rate and so a value of 20% was used instead for this study. It was assumed that the sum of the individual FCIs (Table 5), for the products in the process scheme, would result in the overall FCI (Table 9). As an example, if ethylene were the product of interest, then the overall FCI would be the sum of the individual FCIs for ethanol and ethylene.

Informed decisions on the viability of a product can be made from the NPV, IRR and discounted PBP. Ethylene and HDPE, with their negative NPV and incalculable IRR were discredited as viable products, at least for this scale. In this instance, the FCI and TPC are a sum of the previous steps along the process route as such; there is no production capacity that will enable ethylene or HDPE to break even. This is because the total sales revenue is unable to surpass the increased total CAPEX and OPEX.

[9] Personal communication, Sugar Milling Research Institute, 2016.

Table 8. Economic parameters used in the discounted cash flow (DCF) calculation.

Economic Parameters	Value
Plant Lifetime years	20
Selling Price Inflation (% pa)	3.50
Selling Price:	
Ethanol (R/l)	10.50
Ethylene (R/t)	16 084.03
HDPE (R/t)	21 853.95
LA (R/t)	14 569.30
PLA (R / t)	25 000.00
TPC inflation (% /ann)	1.00
Depreciation Method	MACRS
Income Tax Rate (%)	28.00
MARR (%)	20.00

Table 9. Results of the discounted cash flow (DCF) economic analysis.

Economic results	FCI ($R \times 10^6$)	NPV ($R \times 10^6$)	IRR (%)	Discounted PBP (Years)
PLA	1 932.00	767.26	24.68	10
LA	1 383.87	694.90	25.77	9
Ethanol	300.97	51.14	25.33	16
Ethylene	563.30	-1 498.73	No Value	No Value
HDPE	1 042.64	-1 801.61	No Value	No Value

The PLA, LA and ethanol were accepted as potential products due to their positive NPV and IRR values being greater than the pre-defined 20% MARR. Once the products are accepted, it becomes a question of how to rank them in terms of highest to lowest priorities. The highest priority product would be the first to undergo a rigorous engineering design and economic analysis. It is Important to remember that a product with a minimal capital investment, positive NPV and an IRR greater than the MARR is a viable product up to a point. In context, the ethanol plant had a FCI of R300 970 000, a NPV of R51 140 000 and an IRR of 25.33%. This is the lowest investment and NPV of the accepted products in this case study. Although PLA has the highest NPV of R767 260 000, its FCI is R1 932 000 000. A risk is associated with ranking the ethanol a high priority product, as any inaccuracies or unforeseen circumstances could negatively affect the NPV. The NPV of ethanol would be reduced to zero earlier than the PLA, which has a lot of leeway with its high NPV. On the other hand, the PLA would only be ranked first if the amount of capital available for investment was not less than R1 932 000 000. Further analysis is consequently required to obtain a clearer understanding of the promoted products.

Sensitivity analysis

The sensitivity analysis was performed to quantify deviations from the NPV because of changes in key calculation parameters. As a response to the numerous uncertainties encountered at this early assessment stage of S-BEAT, the FCI, raw material cost and selling price of the products were investigated. The following variations and their effects on the NPV, IRR and discounted PBP were analysed:

- FCI: 0% deviation (baseline), +30% deviation (maximum), -30% deviation (minimum).
- Raw material cost and product selling price: 0% deviation (baseline), +10% deviation (maximum), -10% deviation (minimum).

The extreme cases were taken by increasing all three parameters to either their maximum (worst-case scenario) or minimum (best-case scenario). To assess which uncertainties posed the greatest deviations, the parameters were varied one at a time, whilst keeping the other parameters constant, the results of which are displayed as a Tornado plot (Figure 4).

Figure 2 displays the results of the extreme cases. In the worst-case scenarios, the NPV of ethanol becomes negative, a drastic decrease in the NPV of LA is seen and the NPV of PLA is at its highest. This is indicative of the selling price of PLA having a larger impact on the NPV than the other key parameters. In terms of the range of the NPV values, ethanol < PLA < LA. In terms of the range of the IRR values, PLA is least affected by the sum of the changes applied to it, followed by ethanol and LA. Whilst ethanol appears better than LA, the fact that it becomes unfeasible in its worst-case scenario is a cause for concern.

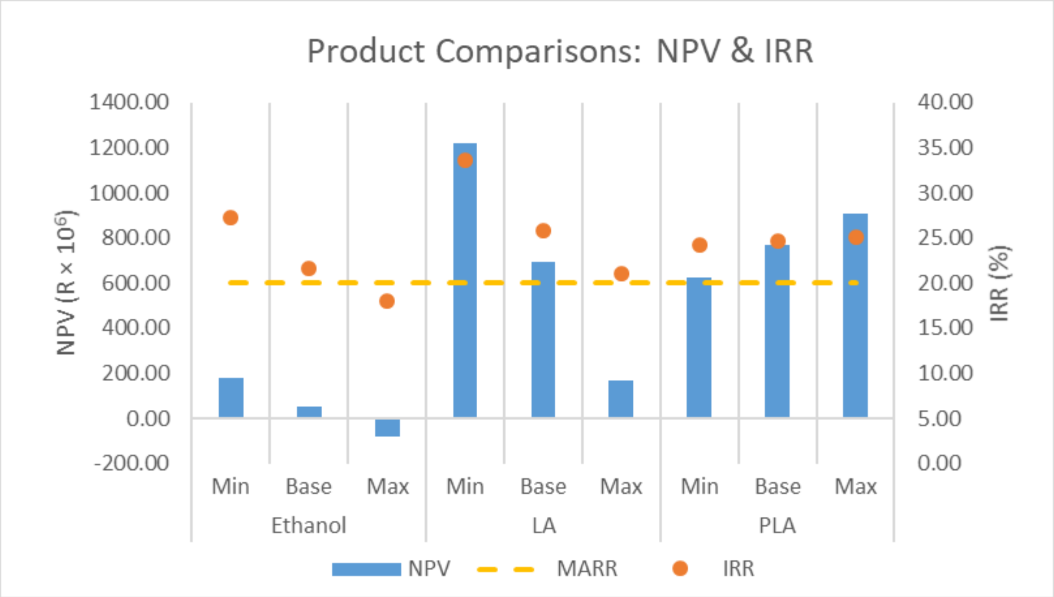

Figure 2. Economic indicators for the minimum, maximum and base cases for ethanol, lactic acid and polylactic acid.

Similar product tendencies as those shown in Figure 2 were noted for the discounted PBP and NPV, presented in Figure 3. Whilst reviewing Figure 3, one would ultimately want a product to fall within the early years with a high NPV. However, variations in the PBP that occur because of the best (min) and worst (max) cases must be considered. Although the best-case scenario of LA has the quickest return with the greatest overall NPV, the associated risk is high. Where inaccuracies are present, the payback period could range from 5 to 16 years. Ethanol ranges from nine years to incalculable for the worst-case scenario, while PLA proves it is the most stable product with it consistently paying out at 10 years. It makes sense that PLA with its similar IRR is comparable with the consistent discounted PBP, as they are both related to a NPV of zero.

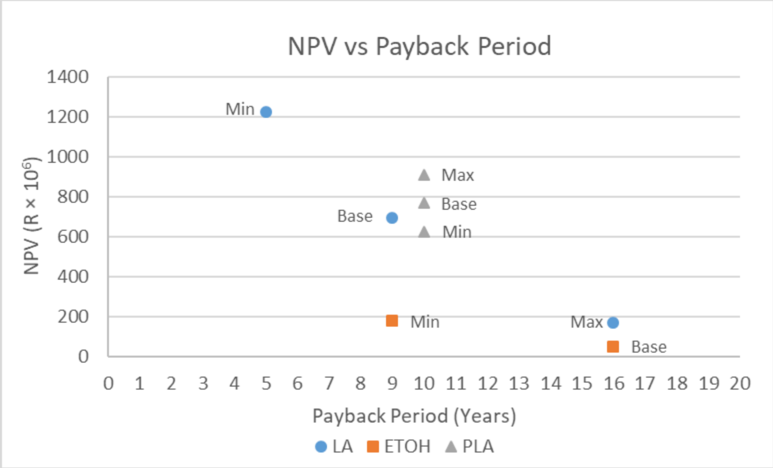

Figure 3. Net present value and payback period for the minimum, maximum and base cases for ethanol, lactic acid and polylactic acid.

Whilst Figures 2 and 3 provide information on the stability of the products when extreme conditions are applied, they do not explain which parameters cause the greatest variability. By recognising this, changes can be made to increase the certainty of the results. The tornado plot (Figure 4) is one means to graphically represent variations in the output (e.g. NPV) dependent on changes in the input parameters (e.g. sales prices, raw material cost and Fixed Capital Investment) (Burk, 2018). The deviations of the maximum and minimum NPV from the baseline NPV values are displayed. The greatest cause of concern for the LA process is its FCI. The FCI is an internal factor; strong deviations can be reduced through more accurate input parameters, or by increasing the accuracy of the calculation method. For LA, investigations should be conducted to determine whether the process parameters can be optimised and a lower FCI achieved. The sales price has the greatest impact on PLA and ethanol. The selling price is an external factor, and greater deviations highlight an important issue: there is a need for reliable policies in South Africa (e.g. import taxes) so that there is a reduction in the operational risks associated with the South African market being the main outlet for the products. The raw material cost is an external factor in the sense of the price of cane being set externally, however, in S-BEAT it is also an internal factor in terms of the calculation procedure for cane juice. The cane juice cost comes second to the selling price of the ethanol process. A significant point is made, that whilst ethanol had the lowest capital investment, along with the lowest NPV, it can become a more feasible product if the market and raw material cost become more beneficial for ethanol production.

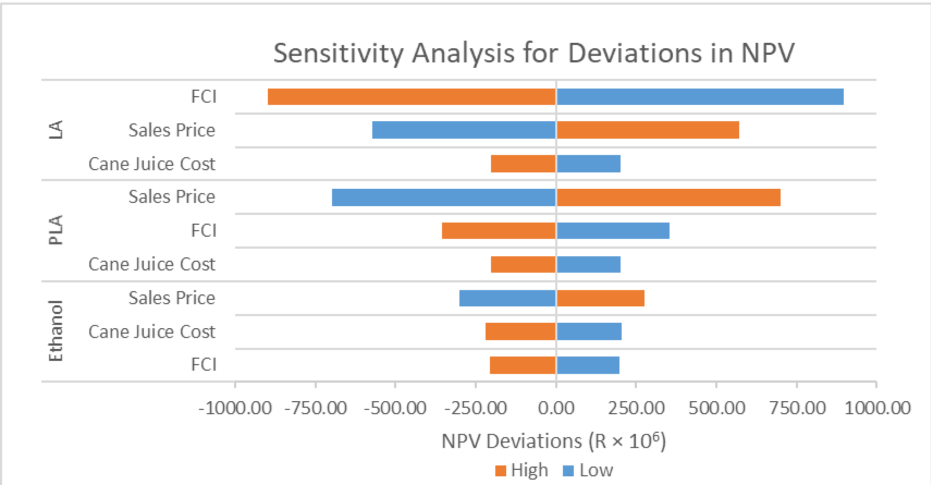

Figure 4. Tornado plot showing deviations to the baseline net present value when the fixed capital investment sales price and raw material costs are varied.

The resulting plots from S-BEAT help in identifying which products perform better than others and under which conditions. Figures 1 and 2 show the performance of the three promoted products and their best and worst-cases, whilst Figure 4 displays the greatest cause for concern within each product. Ranking the products is dependent on the business of interest. If unlimited capital were available, then the PLA, with its consistent performance for the best or worst-case scenario would be the least risky option. If capital were limited, then perhaps understanding the volatility of the sales price would help in accepting ethanol. LA should be considered if the FCI can be more accurately predicted as it is influenced by a controllable factor.

Discussion: S-BEAT

Shortfalls of S-BEAT

Various uncertainties are present within S-BEAT, due to its simplistic OOM approach. The accuracy of the historical information, which is the basis of the calculation, is vitally important. Inaccuracies at this stage would cause errors that propagate throughout the model. The Deloitte Global Manufacturing Competitiveness Index is not meant to be used as a location factor. Nevertheless, the index considers the countries business, economic and social environments serving to define a location factor. The delay of time-sensitive parameters to S-BEAT causes inaccuracies to the results. These various CAPEX related issues can be accounted for with the contingency factor applied to the FCI. It can also be accounted for with a sensitivity analysis to determine which factors have the greatest impact on the product feasibility.

The OPEX calculation is straightforward; however, its dependency on the FCI may cause erroneous results. The operating labour and raw material costs are determined in a simplistic fashion and if actual values are available, they should be used. S-BEAT, at this stage, does not take other raw material costs into account, which could cause under-estimation. The utilities are not based on material and energy balances and the major assumption is that the sugar mill will be able to sustain itself and the biorefinery annexed to it. This is a limitation to the toolbox currently. However, it does not detract from the main goal of S-BEAT which is to be used as a comparative tool for potential biorefinery products, following the NPG Toolbox. The rather simplistic selection of a waste management factor in OPEX is a further limitation, as an unresolved waste management strategy may prove detrimental to process implementation, as is the case for vinasse from ethanol production.

The product revenue is only considered for the main product of interest. The results of the economic analysis could possibly increase if a mixed revenue is calculated for more than just one product. This would be the case if, for example a lactic acid side stream is removed from the PLA process and sold as a secondary product. The sugar revenue should also be added to the cost model as it is implied that sugar will be produced from the remaining mill stream. The many inaccuracies can, however, be considered in the sensitivity analysis by fixing them as the key parameters. The product ranking system has not yet been implemented, as it would be dependent on the specific user.

Adaptability of input parameters and output figures

S-BEAT allows for several input parameters to be tailored to the need of its user. The default parameters, as previously detailed, can be deselected and the user can supply user-values. The feed stream, composition and amounts can be altered. The location factors, cost capacity exponents, raw material costs, product prices and even the OPEX parameters can be replaced. It can therefore accommodate preferences of specific individuals/companies to reflect on their existing product portfolio, internal feedstock costs, established access to various markets etc. Caution must be taken when comparing products; it is necessary to use the same source of information for the case studies undergoing comparisons.

The numerous inaccuracies can be measured by several parameters. S-BEAT allows for the analysis of any of the parameters within it, not only those mentioned in this study. The results can also be visualised based on specific user preference. If the NPV is of greater importance, it will be selected for comparisons. On the other hand, if the IRR is the preferred economic indicator, the sensitivity analysis, tornado plots and overall decision-making will be based on the IRR value.

Conclusions and Future Work

The development of a simplistic method to obtain preliminary cost estimates for a sugarcane biorefinery was achieved with S-BEAT. S-BEAT further allows for the economic comparison of various potential products from sugarcane. The economic indicators utilised in S-BEAT were the NPV, IRR and discounted PBP. They allow for informed decisions to be made on the feasibility of the products of interest. Although many inaccuracies are present within S-BEAT, they can be accounted for with contingency factors and sensitivity analysis. The program is adaptable and the default values can be changed to suit its user. It can hence be concluded that a generic methodology was established with the introduction of S-BEAT, which allows for the speedy comparison of both, different process alternatives and products at a preliminary design stage. The ranking of the various options allows for the selection of products that should be promoted for a more comprehensive, rigorous engineering design.

In future S-BEAT will address the following:

- S-BEAT will incorporate additional streams from the sugar mill to be used as the feed material.
- The loss in potential sugar revenue will be accounted for.
- Scenarios where side streams of the intermediate products will be separately marketed for secondary revenue will be investigated.
- A more statistically rigorous method of estimating the uncertainty of the economic results, will be introduced to S-BEAT.
- A formal system to rank the products from highest to lowest priority will be developed.

Acknowledgements

The authors would like to acknowledge funding obtained through the DST/ Industry public private partnership ‘Sugarcane Technology Enabling Programme for Bioenergy (STEP-BIO)’ – Sector Innovation Fund. The authors thank the SMRI, and specifically S. Davis and K. Foxon for their valuable input and discussions.

REFERENCES

AACE International (2006). *AACE International Recommended Practice No. 28R–03.*

Bonomi A, Cavalett O, da Cunha MP and Lima MAP (2016). *Virtual Biorefinery: An Optimization Strategy for Renewable Carbon Valorisation.* 1st ed. Basel: Springer International Publishing.

Booysen K, Foxon K and Davis S (2017). The development of a screening tool to identify new products for the South African sugarcane industry. *Proc S Afr Sug Technol Ass* 90: 431-454.

Brown T (2006). *Engineering Economics and Economic Design for Process Engineers.* Ohio: CRC Press.

Brown RC and Brown TR (2014). *Biorenewable Resources Engineering New Products from Agriculture.* 2nd ed. Iowa: John Wiley and Sons, Inc.

Burk C (2018). Techno-Economic Modelling for New Technology Development. *CEP:* 43-52.

Chemical Engineering (2017). Economic Indicators: Chemical Engineering Plant Cost Index. *Chemical Engineering*, p 80.

Chikava F (2018). *Economic Recovery of Biobutanol - A Platform Chemical for the Sugarcane Biorefinery.* MSc thesis, University of KwaZulu-Natal.

Daftaribesheli M (2009). *Comparison of Catalytic Ethylene Polymerization in Slurry and Gas Phase.* PhD Thesis. University of Twente.

Deloitte Touche Tohmatsu Limited (2016a). *2016 Global Manufacturing Competitiveness Index.*

Deloitte Touche Tohmatsu Limited (2016b). *Taxation and Investment in South Africa 2016.*

Dias MOS, Cunha MP, Jesus CDF, Scandiffio MIG, Rossell CEV, Filho RM and Bonomi A (2010). Simulation of ethanol production from sugarcane in Brazil: economic study of an autonomous distillery. Pp 733-738 In: Pierucci S and Ferraris GB (Eds.). *Computer Aided Chemical Engineering.* Elsevier.

Dysert L (2003). Sharpen your cost estimation skills. *Cost Engineering* 46(6): 22-30.

Jenkins S (2015). Technology Profile: Production of Polylactic Acid. *Chemical Engineering* p 44.

Kramer K (2013). *Corbion Financials.* Corbion.

Maire Tecnimont (2008). *Facts and Figures 2008.* Maire Tecnimont.

Nel S (2009). The potential of biotechnology in the sugarcane industry: Are you ready for the next evolution? *Proc S Afr Sug Technol Ass* 82: 225-234.

Peters MS and Timmerhaus KD (1991). *Plant Design and Economics for Chemical Engineers.* 4th ed. McGraw-Hill.

Purac Biochem BV (2003). *Method of industrial scale purification of lactic acid*. Netherlands, Patent No. 6630603.

Remer DS and Chai LH (1993). Process Plant Costs of Scaled-up Units. Pp 14-39 In: McKetta JJ (Ed.). *Encyclopedia of Chemical Processing and Design.* New York: Marcell Dekker, Inc.

Richardson Engineering Services (1996). *Richardson's international construction factors: Location cost manual.* Mesa, Ariz: Richardson Engineering Services.

Sinnot RK (2005). *Coulson and Richardson's Chemical Engineering Vol. 6*: Chemical Engineering Design. 4th ed. Oxford: Elsevier Butterworth-Heinemann.

Thomson W (2017). *An economic Analysis of the Potential Bio-based Polymer Industry in South Africa*. MCom thesis, University of KwaZulu-Natal.

Timbuntam W, Sriroth K and Tokiwa Y (2006). Lactic acid production from sugarcane juice by a newly isolated Lactobacillus sp. *Biotechnology Letters* 28: 811-814.

Towler G and Sinnott RK (2012). *Chemical Engineering Design: Principles, Practice and Economics of Plant and Process Design*. 2nd ed. Elsevier Science.

Tran T, Patel T, Iland T, Truong J, Ibidapo-Obe B and Constantino J (2004). *OU Biorefining Technical Report for Biomass Production*, Oklahoma, USA.