



**DEVELOPMENT OF THE SUGARCANE BIOREFINERY
ECONOMIC ANALYSIS TOOLBOX (S-BEAT) AS A
PRODUCT AND PROCESS SELECTION SUPPORT FOR
SOUTH AFRICAN SUGAR MILLS**

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PREFACE

The research contained in this dissertation was completed by the candidate while based in the School of Chemical Engineering of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Howard College Campus, South Africa. The research was financially supported by Sugarcane Technology Enabling Programme for Bioenergy (STEP-Bio), a public: private partnership between the South African sugarcane processing industry and the Department of Science and Technology's Sector Innovation Fund. This work is based on research supported in part by the National Research Foundation of South Africa (grant number: 115465).

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

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DECLARATION 1: PLAGIARISM

I, Prelene Naidoo, declare that:

- 1) The research reported in this dissertation, except where otherwise indicated or acknowledged, is my original work.
- 2) This dissertation has not been submitted in full or in part for any degree or examination to any other university.
- 3) This dissertation does not contain other persons' data, pictures, graphs, or additional information, unless expressly acknowledged as being sourced from other persons.
- 4) This dissertation does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:
 - a) Their words have been re-written, but the general information attributed to them has been referenced
 - b) Where their exact words have been used, their writing has been placed inside quotation marks, and referenced
- 5) Where I have used material for which publications followed, I have indicated in detail my role in the work.
- 6) This dissertation is primarily a collection of material, prepared by me, published as journal articles, or presented as a poster and oral presentations at conferences. In some cases, additional material has been included.
- 7) This dissertation does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the dissertation and in the reference sections.

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DECLARATION 2: PUBLICATIONS

DETAILS OF CONTRIBUTIONS TO PUBLICATIONS

Paper I: Naidoo P, Lokhat D and Stark A (2018). S-BEAT: A preliminary cost estimation method for the sugarcane biorefinery. *Proceedings of the South African Sugar Technologists' Association* 91: 256-274.

The author (Prelene Naidoo) was awarded the Robin Renton Memorial Award by the South African Sugar Technologists Association (SASTA). The award is given to the best “young engineer who shows leadership and management potential, and who delivers a technical paper at SASTA” the judges had this to say:

“Prelene very confidently introduced the S-BEAT (Sugarcane Biorefinery Economic Analysis Toolbox) and demonstrated its usefulness by using it to demonstrate the potential techno-economic benefits of producing HDPE and polylactic acid in a sugarcane biorefinery. The paper was well-written, clearly laid out and introduced sound logic and concepts useful to the sugar industry for costing and assessing biorefining opportunities.”

Paper I was subsequently upgraded to the International Sugar Journal. (See Appendix A)

Paper I: Naidoo P, Lokhat D and Stark A (2019). S-BEAT: A preliminary cost estimation method for the sugarcane biorefinery. *International Sugar Journal* 121(1441): 30 – 40.

Contribution: I designed the study and performed the calculations and analysis of results. I wrote the manuscript with suggestions and contributions from Prof. Anne Stark and Dr David Lokhat.

Paper II: Naidoo P, Lokhat D and Stark A (2019). S-BEAT: Extending the inventory of the sugarcane biorefinery economic analysis toolbox to other sugar mill feeds and products. *Proceedings of the South African Sugar Technologists' Association* 92: 226-244.

The author (Prelene Naidoo) was awarded the 2019 Student Award by the South African Sugar Technologists Association (SASTA). The award is given to “The student who writes and delivers the best paper at Congress.” the judges had this to say:

“This paper has high value to the industry because it provides a toolbox to allow financial analysis of potential new sugarcane-derived products which is critical for investment decisions. The paper was confidently presented.”

Contribution: I designed the study and performed the calculations and analysis of results. I wrote the manuscript with suggestions and contributions from Prof. Anne Stark and Dr David Lokhat.

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ABSTRACT

In recent years, key stakeholders within the South African Sugar Industry have realised the necessity to diversify their product portfolios further and move from only sugar-based products to the production of chemicals, materials, and fuels. Numerous value-added products can potentially be generated from the available streams in a sugar mill. In theory, these products can supply numerous markets of various sizes and hence generate new revenue streams for the sugar mill. A toolbox, the Sugarcane Biorefinery Economic Analysis Toolbox (S-BEAT) which uses a preliminary cost estimation method, was developed to serve this purpose. S-BEAT provides both a cost estimation and economic analysis at a preliminary process design stage for preselected product and process alternatives in the South African context.

S-BEAT makes use of the order of magnitude approach, which is based on data from 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 $\pm 30\%$ to $\pm 50\%$, which is considered satisfactory for a preliminary cost estimate. The cost estimates then undergo an economic analysis to determine product profitability (Net Present Value (NPV), Internal Rate of Return (IRR) and Discounted Payback Period). S-BEAT allows for a comparison between process and product alternatives, as well as between raw material type (clear juice, mixed juice, syrup, A-sugar, or A-molasses) and quantity (effects of economies of scale) of a sugar mill stream diverted from sugar production to the biorefinery operation. Furthermore, it comprises a sensitivity analysis option which is used to identify those process variables that exhibit the largest effect on the overall economics, serving as pointers for specific process optimisation.

With this toolbox, a techno-economic analysis of several products, including high-density polyethylene (HDPE), polylactic acid (PLA), monoethylene glycol, lysine, succinic acid, 1,4-butanediol and 2,5-furandicarboxylic acid, was conducted. The economics, in the form of the NPV, IRR and Discounted Payback Period, from the aforementioned raw material streams were assessed. Additionally, the Minimum Selling Price that is required to ensure a plant is feasible is included for a range of feedstock costs and numerous plant capacities.

The results of this assessment are presented comparatively and provide a basis for decision making for the local sugar industry on which processes and products should be further investigated at a more rigorous techno-economic modelling level.

The S-BEAT toolbox is available to the South African Sugar Industry to assess products using in-house specific data. Further products and feedstock streams can be added, to support decision making at this early stage of the industry's transformation to a diversified industry.

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NOMENCLATURE

1,4-BDO	1,4-Butanediol
AACE	Association for the Advancement of Cost Engineering
ACostE	Association of Cost Engineers (UK)
ANSI	American National Standards Institute
BioPET	Biorenewables Process Evaluation Tool
CAPEX	Capital Expenditure
CEPCI	Chemical Engineering Plant Cost Index
CJ	Clear Juice
DCF	Discounted Cash Flow
DST	Department of Science and Technology
EtOH	Ethanol
FCI	Fixed Capital Investment
FDCA	Furan dicarboxylic acid
FPC	Fixed Production Cost
GBL	Gamma-butyrolactone
GDP	Gross Domestic Product
GE	General Expense
HDPE	High-Density Polyethylene
IRR	Internal Rate of Return
LA	Lactic Acid
MACRS	Modified Accelerated Cost Recovery System
MAN	Maleic Anhydride
MARR	Minimum Acceptable Rate of Return
MEG	Monoethylene glycol
Mol	Molasses
MSP	Minimum Selling Price
NPG	New Products Greenhouse
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
OOM	Order-of-magnitude
OPEX	Operational Expenditure

PBP	Payback Period
PBS	Polybutylene Succinate
PBT	Polybutylene Terephthalate
PLA	Polylactic Acid
RV	Recoverable Value
SA	Succinic acid
SASA	South African Sugar Association
SASTA	South African Sugar Technologists Association
S-BEAT	Sugarcane Biorefinery Economic Analysis Toolbox
SCENT	Standardised Cost Estimation for New Technologies
SMRI	Sugar Milling Research Institute NPC
SP	Selling Price
STEP-Bio	Sugarcane Technology Enabling Programme for Bioenergy
TCI	Total Capital Investment
THF	Tetrahydrofuran
TPC	Total Production Cost
TRL	Technology Readiness Level
USD	US Dollar
USGC	The United States Gulf Coast
VPC	Variable Production Cost
WC	Working Capital
WEF	World Economic Forum
ZAR	South African Rand

CHAPTER 1: INTRODUCTION

1.1 Rationale for the research

The South African Sugar Association (SASA) has stated that “The South African Sugar Industry is one of the world’s leading cost-competitive producers of high-quality sugar, ranking in the top 15 out of approximately 120 sugar-producing countries worldwide.” The combination of sugarcane cultivation and raw and refined sugar production contributes approximately R 16 billion (SASA, 2018) to the national Gross Domestic Product (GDP). Table 1.1 was adopted from SASA (2018), and it depicts the number of direct and indirect jobs that are associated with the sugar industry.

Table 1.1: Key factors in the South African Sugar Industry (adapted from SASA, 2018)

	Values
Number of sugarcane farmers	22 500
Area under cane (ha)	365 000
Number of sugar mills	14
Direct jobs	85 000
Indirect jobs	350 000
Contribution to GDP (Gross Domestic Product)	R 16 billion

In recent years, the industry has faced challenges due to drought, lack of transformation, importation issues, pricing concerns and the recent implementation of the Health Promotion Levy (Government of South Africa, 2019). The South African parliament has acknowledged these challenges and is currently working with the sugar industry to improve the existing situation (Azzakani, 2019). One of the long-term solutions that has been proposed to aid with these many, complex challenges has been product diversification through biorefineries (Government of South Africa, 2019).

A biorefinery has been defined by the American National Renewable Energy Laboratory (NREL) as a “facility that integrates biomass conversion process and equipment to produce fuels, power and chemicals from biomass” (Kamm *et al.*, 2006). A sugar mill has the potential to become a profitable biorefinery as the existing infrastructure, labour and utilities can be modified and/or expanded as required. Figure 1.1: A selection of some of the potential products which can be derived from biomass (adapted from Kamm *et al.* (2006)) has been adopted from Kamm *et al.* (2006) and illustrates the complex network of products which arise from a biomass feedstock. From Figure 1.1: A selection of some of the potential products which can be derived from biomass (adapted from Kamm *et al.* (2006)), it can be seen that a broad product portfolio is available for a sugar-based biorefinery. However, this raises the question regarding which product/s would be most viable for integration.

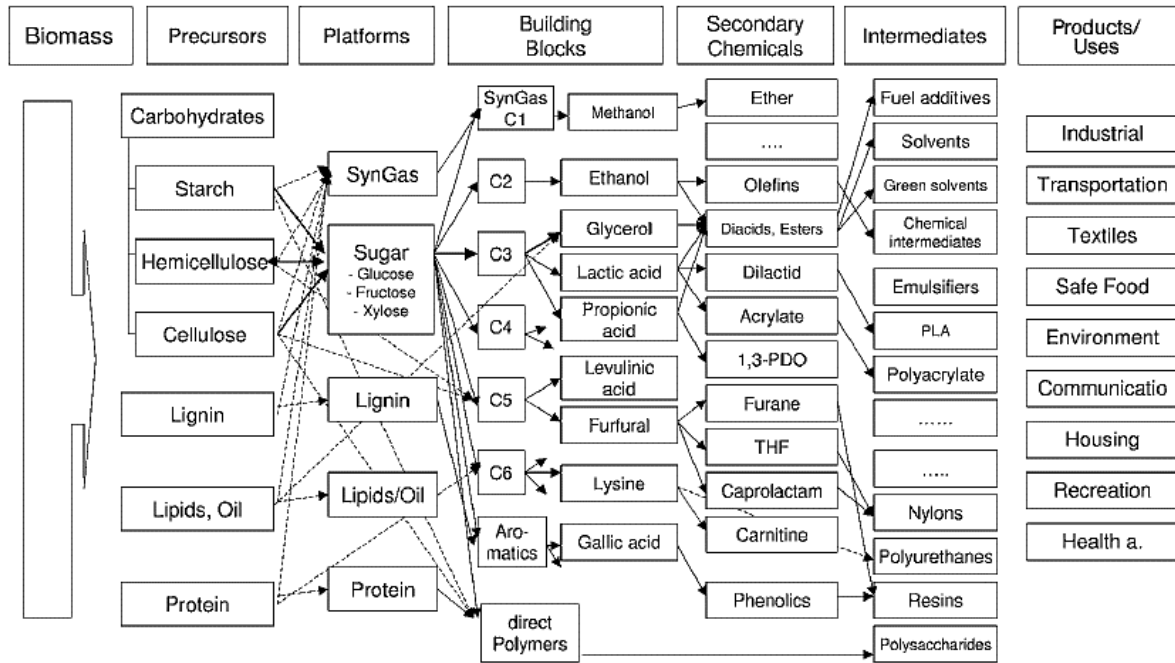


Figure 1.1: A selection of some of the potential products which can be derived from biomass (adapted from Kamm et al. (2006))

The Sugar Milling Research Institute NPC (SMRI) established a public: private partnership between the South African sugarcane processing industry and the Department of Science and Technology's Sector Innovation Fund to form the Sugarcane Technology Enabling Programme for Bioenergy (STEP-Bio) between March 2015 and March 2019. *Biorefinery modelling and new products development* was one of the subprojects which fell under the STEP-Bio programme. The overall aim of this project was the development of decision-support tools and techno-economic models that would direct research efforts onto projects which maximise on profitable opportunities and subsequently the overall progression of the South African Sugar Industry (Davis, 2014).

A subset of the projects which fell within the biorefinery modelling and new products development subproject was first to establish an integrated and validated sugar, ethanol, and cogeneration model. A MATLAB® model was developed by Mathew Starzak and Steve Davis (Starzak and Davis, 2017), and subsequently converted into an Aspen Plus® model by Kylan Guest (Guest, 2018). The intention was to create a generic mill model as the basis for biorefinery operations modelling. MATLAB® and Aspen Plus® are commercial software which require licenses for use. It was decided that a more accessible platform should be considered for the earliest stage of design, where products are being screened. The New Products Greenhouse (NPG) Toolbox was developed by Kim Booyesen of the SMRI as a bioproduct screening tool for the sugar industry. The tool was created on the Microsoft Excel platform. It is easy to use and can be accessed by a wider range of interested parties. The tool uses built-in algorithms to rank the commercial feasibility of new products (Booyesen *et al.*, 2017). Whilst the tool proves to be extremely beneficial for a preliminary selection, it lacks an economic assessment of the

products, which is imperative to any decision-making process. Cost estimations are of paramount importance for the consideration of any project and their process alternatives. Considering that investments are required for the development of a new biorefinery, it is necessary to determine the economic viability of the project before any important decision can be made and to compare between different product and process options. The Sugarcane Biorefinery Economic Analysis Toolbox (S-BEAT) developed for this purpose is presented in this thesis.

1.2 Status of existing methods used in preliminary cost estimations of biorefineries

Studies have been conducted on which methods should be applied to obtain reasonable cost estimates for a biorefinery processing plant (Cheali *et al.*, 2015; Tsagkari *et al.*, 2016). Tsagkari *et al.* (2016) performed a comparative study on the various heuristic techniques that can be employed in the capital cost estimation of biorefinery processes during their early stage of design. They suggested that the classification of capital cost estimates has not yet been universally standardised. However, they consolidated information into a table on the different classification practices (Table 1.2). In Table 1.2, a comparison of the expected accuracy for each level of classification as described by the Association for the Advancement of Cost Engineering (AACE), the American National Standards Institute (ANSI) and the Association of Cost Engineers (UK) (ACostE) is presented. Additionally, the Technology Readiness Level (TRL) as identified by the European Commission, is given for each class of estimation. The TRLs are used as a metric system for the evaluation of the progress in research and development, the comparison of different technologies and to allow for the maturity status of a technology to be defined (Tsagkari *et al.*, 2016). According to Table 1.2, it is appropriate to use the Order-of-Magnitude method during the early stages of a project's development (TRL 1 - 4). More detailed calculations are required as a project progresses from the conceptual phase to operation. Additionally, Table 1.2 suggests that an Order-of-Magnitude estimate should use data from a project that is classified as TRL 7 - TRL 9, as the input data would be more accurate.

Table 1.2: A comparative table of the classification practices used in capital cost estimations reproduced from Tsagkari *et al.* (2016)

AACE std.	ANSI std. Z94.0	ACostE	TRL
Class 5 Low: -20 to -50 % High: +30 to +100 %	Order-of-Magnitude -30 / +50 %	Order-of-Magnitude Class IV -30/ +30 %	TRL 1-4 Technology conception, laboratory validation
Class 4 Low: -15 to -30 % High: +20 to +50 %	Budget -15/ +30 %	Study Class III -20 / +20 %	TRL 5-6 Technology validation and demonstration
Class 3 Low: -10 to -20 % High: +10 to +30 %		Budget Class II -10/ +10 %	TRL 7 Operational system demonstration
Class 2 Low: -5 to -15 % High: +5 to +20 %	Definitive -5/ +15%	Definitive Class I -5/ +5 %	TRL 8 System contemplation and qualification
Class 1 Low: -3 to -10 % High: +3 to +15 %			TRL 9 Actual system operation

The purpose of the different classes and their typical cost estimation methods, for the AACE standards, are adapted from Christensen and Dysert (2011) and elaborated on in Table 1.3.

Table 1.3: Purpose of the AACE standards and their typical costing methods per class (adapted from Christensen and Dysert (2011))

Estimate Class	Purpose of Estimate	Typical Costing Method
Class 5	Concept screening	Order-of-Magnitude
Class 4	Preliminary	Equipment factored or parameter models
Class 3	Budget authorisation	Detailed unit cost
Class 2	Budget control	Costs from the contractor
Class 1	Construction	Costs from the completed design and bidding

Tsagkari *et al.* (2016) suggested that for an order-of-magnitude capital cost estimate of a process, a researcher would require an escalation factor of a similar process and an equipment list or a conceptual block diagram of the major processing steps. The heuristic techniques that can then be employed are power-law/ exponential estimating, factorial estimating and significant processing step estimating (Tsagkari *et al.*, 2016).

The power-law/ exponential estimating method can be used when historical information is available for a processing plant and is often described by equation 1. The cost of the new plant is based on the cost of the historical plant with an adjustment that is made for different capacities.

$$\frac{c_1}{c_2} = \left(\frac{S_1}{S_2}\right)^p \times t \quad (1)$$

Subscripts 1 and 2 refer to the proposed and existing plants, respectively, C is the cost of the plant, S is the size or capacity of the plant, p is an exponent which is used to account for economies of scale and t is a correction factor which escalates the historical plant to the correct time frame and location of the

new plant. Several factors are available for p to describe different equipment types, products, or processes. However, an average of 0.6 is often used (Tsagkari *et al.*, 2016).

The factorial estimating method was originally described by Lang (1947), who stated that the capital investment of a plant could be calculated by applying a factor f (the Lang Factor) to the purchased equipment cost of the plant. A detailed equipment list and the necessary costs are therefore required for this method. The equipment cost can be obtained through calculations using design information, vendor quotations or from published data (Cheali *et al.*, 2015). The Lang Factor is dependent on the type of process under investigation: solids, fluids, or solid-fluids. Tsagkari *et al.* (2016) also discussed the contributions and modifications made by various authors to the original Lang factorial estimating method.

The significant process step estimating method or functional unit method requires a large amount of information. The method states that the capital cost of a plant is a function of the plant's major processing steps and various parameters which are used to describe these processing steps: capacity, throughput, temperature (max/min), pressure (max/min) and construction materials (Tsagkari *et al.*, 2016).

Several methods and tools have been developed to assess the economics of both new processes, as well as those of existing processes under a new set of conditions. Crous (2010) developed a Microsoft Excel-based program, with an algorithm that can vary and compare different biorefinery process alternatives and raw material feedstocks to obtain the same biorefinery product. The program calculates the capital and operating cost estimates for the process configuration as well as the energy and steam requirements. The capital investment is calculated according to the factorial estimating method. The equipment costs are escalated according to the Marshall and Swift index, and a user-defined factor is applied to adjust the location of the plant. The operational expenditure is calculated with the methods of Sinnott (2005), and the economics of each scenario are presented in the form of the Net Present Value.

The Standardised Cost Estimation for New Technologies (SCENT) tool was described by Ereev and Patel (2012) as a method which can cost new or emerging technologies for which limited information is available. SCENT uses the factorial estimating method to calculate that capital investment. The overall objective of the Microsoft Excel-based model was to obtain the total production costs of the manufacturing process being investigated. The method applies the equipment costs as presented by Woods (2008) and escalates it to the current year with the Chemical Engineering Plant Cost Index (CEPCI). A labour related installation factor is used to describe the difference between installing the equipment in the United States and any other country of interest. The operational expenditure employs

factors as presented by Peters *et al.* (2003). The operating labour is calculated using the approach by Ulrich (1984), which contains a table of common equipment and the operators that are required per equipment.

Claypool and Raman (2013) developed the Biorenewables Process Evaluation Tool (BioPET), which is also a Microsoft Excel spreadsheet-based early estimation tool. BioPET has fermentation, separation, and purification unit operations with the required modelling equations and parameters per unit programmed into it. The user enters the necessary input values to obtain a final capital cost of the unit. The operating costs for the utilities, feedstock and other materials like solvents and catalysts are predefined, and the operating labour and the remainder of the fixed costs are calculated as a percentage of the capital cost. The calculation of the general expenses is based on the total production cost. The final result of BioPET is an estimate of the minimum selling price that is required for the product of interest. A sensitivity analysis of the production capacity and the feedstock cost affecting the product selling price is also performed.

The tools discussed above are especially useful for their specific purpose, which is to generate a preliminary cost and economic estimate of new processes. Their methods can be categorised as Class 4 of Table 3, which makes use of equipment factored or parameter models to obtain preliminary cost estimates. Whilst these tools are beneficial to certain users, it was considered to be important to develop a tool which can generate an economic analysis for several products in a timely fashion, and which is specific to the South African Sugar Industry.

It was recommended that a research tool be developed which investigates products and processes with high technology readiness levels, established technologies and markets. This could be done based on appropriately adjusting the costs of existing biorefinery facilities. However, these processes are relatively new and do not disclose detailed information, including the cost of their major equipment. It is, therefore, more appropriate to develop a tool which employs an order-of-magnitude approach like the exponential estimating method (Class 5 of Table 3), to achieve the conceptual screening of processes to serve this purpose. The technique that was described for the operational expenditure of the previously mentioned tools would still be valid for Class 5 capital cost estimates. However, adjustments would be required for the raw material cost, operating labour, and utilities, so that the resulting costs are specific to the South African Sugar Industry.

1.3 Justification, aims and objectives

The aims identified as pivotal to the definition of this work were firstly that the sugar industry requires assistance in determining which products should be investigated in detail for the integration of a biorefinery with their respective sugar mills. Secondly, whilst the NPG tool considers feedstock competition, market, technology, and some economic criteria in its screening approach for potential bio-based products (Booyesen *et al.*, 2017), it does not provide capital and operational expenditure and economic indicators to make an informed decision on which products to investigate. This is the purpose of the Sugarcane Biorefinery Economic Analysis Toolbox (S-BEAT) presented herein. S-BEAT provides decision making support for products or processes, which are to be further investigated in depth using Aspen Plus® models.

In parallel to S-BEAT, as another sub-project of the STEP-Bio programme, a MATLAB® model was converted to an Aspen Plus® model of the generic sugar mill (Guest, 2018). On one hand, process stream data of the Aspen Plus® sugar mill model feeds information to S-BEAT (stream composition and volume flows). On the other hand, it also serves as a basis for downstream Aspen Plus® modelling of the products and processes that generated positive economic outlooks in S-BEAT's order-of-magnitude pre-screening. Hence, S-BEAT fulfils one of the goals of the STEP-Bio programme, i.e., to provide a techno-economic analysis tool which aids in the comparison and selection of new products which would subsequently be promoted to a more rigorous process design and complete business case study.

The main research question, reflecting the aim, was hence: How can a preliminary cost estimation method be implemented into an easy-to-use tool, for diversification projects in the South African Sugar Industry, that can provide the CAPital EXpenditure (CAPEX), OPerational EXpenditure (OPEX), as well as an economic analysis and comparison of various bioproducts and process alternatives? A secondary aim was to design the tool such that additional products and processes could be included in future research. Furthermore, an extension to other feedstock streams should be possible.

The objectives of this work were the following:

- To design a platform which should be easy to use, guiding the user to provide the relevant input when assessing a new product, while standardising other parameters and assumptions using the same assessment routine. This was deemed essential to enable the comparison between products and processes at a similar level of certainty.
- To identify and apply capital and operational cost estimation methods to obtain a conceptual order-of-magnitude estimate of various biorefinery processes existing elsewhere, at a typical SA sugar mill capacity, taking SA specific costs into account.

- To calculate and make use of well-known economic indicators to make an informed decision on which products will be economically beneficial to the sugar industry.
- To incorporate a routine for economic analysis and comparison of different biorefinery products, including a sensitivity analysis.
- To conduct a techno-economic assessment for several potential biorefinery products to demonstrate the capabilities of the toolbox.
- To quantify the uncertainties that are present in the results of S-BEAT due to the preliminary estimation method, the uncertainty in biomass and bio-product price. To use the uncertainty when analysing which products are feasible or not.

1.4 Outline of the dissertation structure

Chapter 2 provides a review of relevant literature. The advantages of sugarcane biorefineries are detailed, the South African Sugar Industry and the obstacles the industry has faced in recent years are introduced. Techno-economic assessments and uncertainties that are prevalent in decision making are touched on as well as the approaches that have been taken in the early stage of biorefinery design.

Chapter 3 and Chapter 4 contain two papers that were presented at the Congress of the South African Sugar Technologists' Association in 2018 and 2019, respectively. Chapter 3, which is based on paper 1, focusses on describing the methods that are incorporated in S-BEAT providing case studies for five different products: ethanol, ethylene, high-density polyethylene, lactic acid and polylactic acid. It further discusses the pros and cons of S-BEAT (Naidoo *et al.*, 2018).

Chapter 4 (paper 2) is an extension of chapter 3 (paper 1), whereby the effect of using different mill streams (stream cost and capacity) on economic performance is considered. Furthermore, several additional products were assessed. Chapter 4 also compares the economics of various products produced from either the same or different mill streams and presents an overall summary of the product profitability as investigated by S-BEAT (Naidoo *et al.*, 2019). Additionally a discussion of the differences between papers 1 and 2 was included at the end of chapter 4.

Chapter 5 defines the assumptions, limitations, decisions, and discussions surrounding the development of S-BEAT. Pseudocode diagrams are used to demonstrate the logical progression of the toolbox, which are accompanied by a user manual (Appendix B). Features not demonstrated in Chapter 3 and 4 that were incorporated into S-BEAT are described, one of which was the implementation of a minimum selling price seeker. The minimum selling price (MSP) seeker automatically generates the MSP that would be required to obtain an IRR of 20% for a range of feedstock costs and plant throughputs. In

keeping with the format of the previously published papers, three case studies were presented, including a discussion on how uncertainties in market price and size affect the uptake of new products.

Chapter 6 concludes this work and an outlook for further work was also provided.

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CHAPTER 2: LITERATURE REVIEW

2.1 The biorefinery concept

The following definitions have been used to describe a biorefinery:

- The American Department of Energy (DOE): “A biorefinery is an overall concept of a processing plant where biomass feedstocks are converted and extracted into a spectrum of valuable products. Its operation is similar to that of petrochemical refineries.” (Kamm *et al.*, 2006)
- The American National Renewable Energy Laboratory (NREL): “A biorefinery is a facility that integrates biomass conversion processes and equipment to produce fuels, power, and chemicals from biomass. The biorefinery concept is analogous to today’s petroleum refineries, which produce multiple fuels and products from petroleum. Industrial biorefineries have been identified as the most promising route to the creation of a new domestic biobased industry.” (Schieb *et al.*, 2015)
- The International Energy Agency (IEA): “Biorefinery is the sustainable processing of biomass into a spectrum of marketable products (food, feed, materials, chemicals) and energy (fuels, power, heat)” (de Jong *et al.*, 2020).

According to Kamm and Kamm (2004), there are three types of biorefineries. Fixed processing capabilities and fixed products and feedstock define a phase I biorefinery, for example, it can only produce ethanol from a fixed feedstock. A phase II biorefinery has more processing flexibilities and can produce various end products depending on the market demand. An example would be the production of lactic acid and polylactic acid from sucrose. A phase III biorefinery can use a mixture of biomass feed materials, many processing technologies can be combined, and it can produce low-value products in high volume, and high-value products in low volume (Kamm and Kamm, 2004).

The most beneficial operation of a biorefinery occurs when multiple factories operate on one site as a single industrial entity. The factories supply each other with the necessary feedstock and energy requirements. The entire integrated biorefinery can minimise losses and optimise profits by considering the upstream and downstream product markets simultaneously. Ultimately, the viability of a biorefinery increases with increased integration (Schieb *et al.*, 2015). Aristizabal-Marulanda and Cardona Alzate (2018) captured the advantages of an integrated over a stand-alone biorefining facility. They stated that the biorefinery production costs and hence the product selling prices were reduced due to the variety of saleable products. Furthermore, if the co-products of the biorefinery are of high value and low volume, the main product selling price can be reduced. As a consequence of integration, it is possible to run co-products of low volume and high value at a lower cost than if the low volume and high-value process had been stand-alone.

Mass and energy integration between processes in the biorefinery is beneficial. By assessing the various markets and demands of the main product and the co-products, the problems associated with market-related conditions and price fluctuations can be minimised (Aristizabal-Marulanda and Cardona Alzate, 2018). Cardona-Alzate *et al.* (2020) suggested that true representations of a biorefinery, which uses a biomass source to produce a range of different products, have in fact not been operational but instead companies have opted to operate stand-alone biorefineries, despite the advantages of a diversified biorefinery.

An oil refinery operates to produce different chemical products and fuels from oil. In the same way, a biorefinery produces a multitude of bio-based chemicals and biofuels from biomass. In fact, biorefineries compete with oil refineries because they could potentially produce materials which have comparable properties and applications of products from an oil refinery (Schieb *et al.*, 2015). There are two types of bio-based products: the chemically identical version of a petrochemical product, in an established market, is known as a drop-in bio-based product. The second type, a so-called “dedicated bio-based product”, however, can only be produced from a bio-based feedstock and does not have a fossil-based counterpart (Werpy and Peterson, 2004).

Examples of drop-in products include ethylene, polypropylene, polyethylene, and polyethylene terephthalate. Examples of dedicated bio-based products include levulinic acid, lactic acid, succinic acid and polylactic acid. On occasion, a drop-in or dedicated bio-based product can be produced from a combination of bio-based feedstocks and fossil-based feedstocks, like in the instance of polyethylene terephthalate (Spekreijse *et al.*, 2019). Table 2.1 was adapted from Werpy and Peterson (2004), who provided advantages and disadvantages of dedicated and drop-in products along with an additional category for intermediate building blocks.

Table 2.1: Characteristics of drop-in, dedicated and intermediate products, adapted from Werpy and Peterson (2004)

	Drop-in Product	Dedicated Products	Intermediate Building Blocks
Characteristic	Competes with existing petrochemically derived chemicals and products	New and improved properties that can replace existing products or can be used for new applications	A diverse portfolio of products results from a single intermediate product
Examples	Acrylic acid from propylene or lactic acid	Polylactic acid, from glucose-derived lactic acid	Succinic acid, levulinic acid, glutamic acid, glycerol, syngas
Advantages	Existing markets, cost structure and growth potential are understood, reduced market risk	Cost issues are less critical with novel products, no competition with petrochemical routes, differentiation is based on the desired performance, new market opportunities, most effective use of inherent biomass properties	Product swing strategies can be used to reduce market risks; the market potential is expanded, capital investments can be spread over many operations, advantages of both drop-in and dedicated products are incorporated
Disadvantages	Competing on costs, competing against depreciated capital, limited “market differentiation” for biobased vs petrochemical-based sources	Capital risks are high, time to commercialisation is high. Markets are not clearly defined	Identifying what to focus on in research and development

According to Aristizabal-Marulanda and Cardona Alzate (2018), one of the most considerable differences between an oil refinery and a biorefinery is that the petrochemical industry has a high maturity level of technologies and the feed supply is typically continuous. The technologies that are required to operate an integrated multiple product biorefinery are currently at a lower technology readiness level. The biomass is often seasonal and would require additional stabilisation if it is to be held in storage to ensure the material does not undergo chemical decomposition (Aristizabal-Marulanda and Cardona Alzate, 2018).

2.2 Sugarcane biorefineries

Many biomass materials are available for use as a feedstock in the production of biofuels and bioproducts. These include sugar crops, starch crops, lignocellulosic crops and residues, organic residues, perennial grasses and legumes, oil crops, and aquatic biomass (O’Hara, 2016). Sugarcane, a sugar crop, has been acknowledged as one of the most suitable feedstocks for large-scale commercialisation of biomass into biofuels and bioproducts (O’Hara, 2016).

The sugar industry, as it stands, operates as a biorefinery where multiple products are generated from a single biomass source (Robins and Speight, 2016). Crystal sugar, molasses for animal feed or ethanol

production, and bagasse, which is combusted to produce combined heat and power, are some of these products. If the biorefinery generated additional products to supply the fine and/or chemical commodity markets then it could have more operational flexibility by ramping up production of different product streams under favourable market conditions, greater revenue would be generated, and waste streams that would have been discarded would become valuable.

Numerous intermediate streams are produced during the conversion from sugarcane to crystal sugar, bagasse, and final molasses. These streams include mixed juice, clear juice, syrup, and intermediate stage molasses. Each intermediate stream that can be integrated with a bioprocess has a different purity and cost associated with it, and this is depicted in Figure 2.1. Whilst the cost of the intermediate streams is not explicitly documented in literature, the stream value increases as additional effort and cost are expended in processing, and as the sucrose content increases along the processing route (Robins and Speight, 2016).

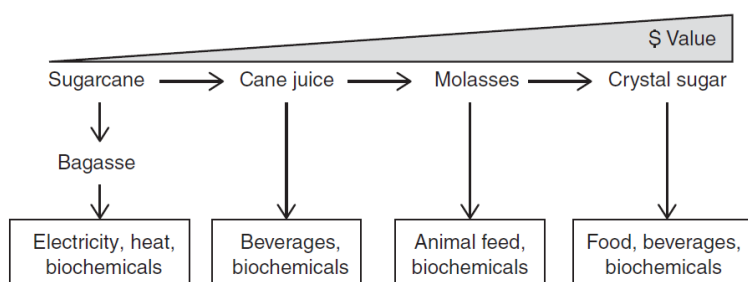


Figure 2.1: Representation of intermediate streams increasing in value from sugarcane to crystal sugar, adapted from Robins and Speight (2016)

The feasibility of a process that makes use of sucrose as the feed material will be impacted by the high price fluctuations that sugar, which is a globally traded commodity, experiences. Consider that a bio-based product price is often determined by market conditions, i.e., by customer demand and the price of the product's petrochemical counterpart instead of by the raw material and manufacturing costs of the product. Suppose the market price of the bio-based product was low, and the raw material cost (the sugar) was too high. In that case, the entire process could become unfeasible as the manufacturing costs could exceed the sales revenue (Robins and Speight, 2016). The challenge would be to find the balance between the supply volume of the raw material and the demand for the product that would not saturate the market and inevitably bring the product price down.

On the other hand, a low sugar price would result in less revenue generated from sugar production, and the overall economics of the sugar biorefinery could be feasible if a high-value chemical product is produced. To summarise, sugar should be sold when the sugar price is high whilst a high-value bio-based product should be sold when the sugar price is low to ensure a feasible biorefinery (Robins and

Speight, 2016). The intermediate streams in the sugar mill would inherently be affected by the sugar price as well, which means that the feasibility of extracting an intermediate sucrose stream would also be dependent on whether the sugar price is high or low (Robins and Speight, 2016).

Sugarcane bagasse is traditionally used to generate heat, steam, and power for the sugar mill. Through cogeneration, a sugar mill can also supply electricity to the surrounding grid. Bagasse, however, can also be used as a feed material for bio-based product generation. A biorefinery which uses sugarcane bagasse as the feed material is known as a lignocellulosic biorefinery. If all of the bagasse were to be diverted to chemical production, then it would have to be supplemented by an alternative energy source such as coal (Robins and Speight, 2016). This increases the operational expenditure of both the sugar mill and the appended biorefinery and needs to be taken into consideration. It is therefore important to determine, during the early design, testing and piloting stages, which source of the mill stream can be used as the biomass feedstock, as there are vast differences regarding sugar concentrations, purities, and stream costs.

2.3 The South African Sugar Industry

2.3.1 Key players

In South Africa, statutory powers of self-governance are given to the sugar industry as per the terms of the Sugar Act, 1978 and Sugar Industry Agreement, 2000. The South African Sugar Association (SASA) is the statutory body, and it falls under the authority of the Department of Trade and Industry (Conningarth Economists, 2013). SASA provides the following services to support the industries partnerships: it ensures compliance to industry legislation, audits the cane payment system, and determines the industry proceeds for the calculation of the cane payment system. It provides support to maintaining and growing the local sugar market, manages industry finance, the industry's relationships with external stakeholders, the export market of raw sugar, and the development of policy on land reform (SASA, 2020). Figure 2.2 provides the structure of the South African Sugar Industry.

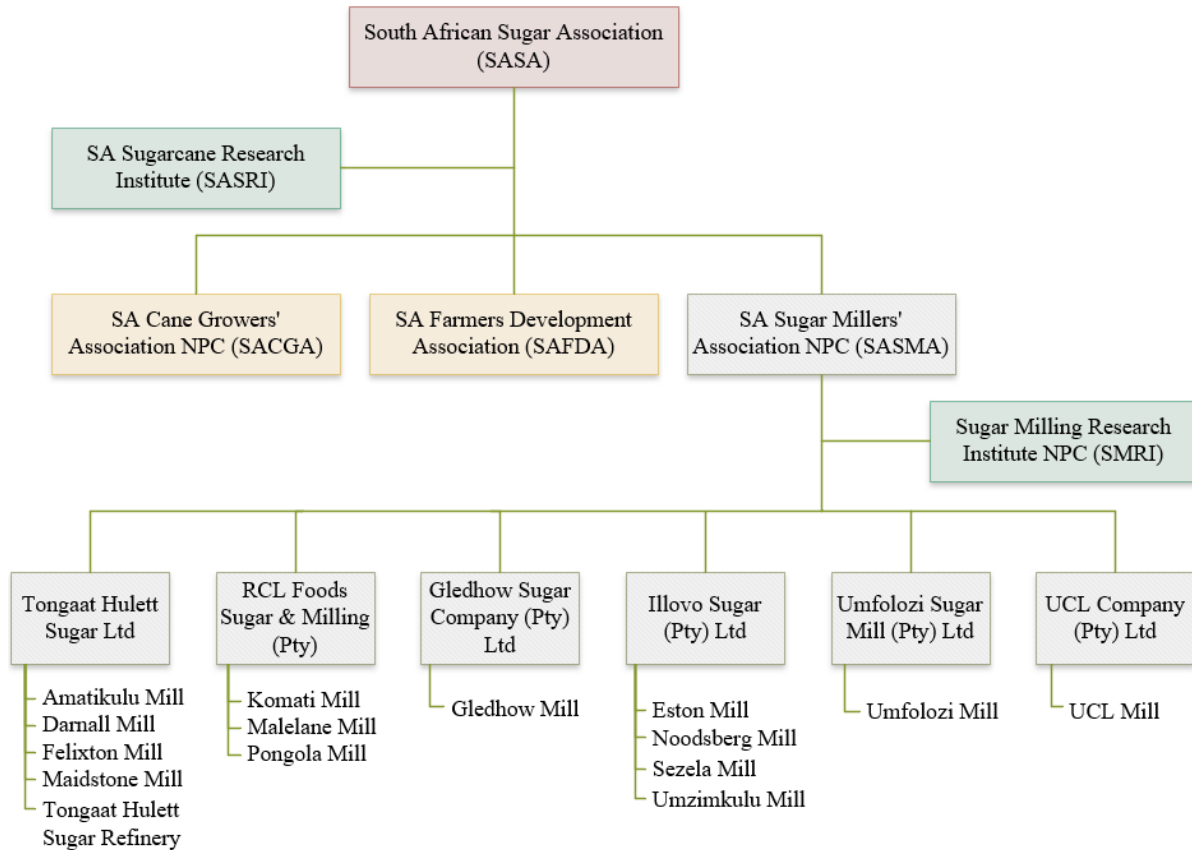


Figure 2.2: Graphical representation of the structure of the South African Sugar Industry, information was obtained from SASA (2019)

SASA distributes the revenue that is generated by the sugar industry to the growers and the millers. The local and export sugar and molasses sales make up the total industrial proceeds from which SASA deducts their industrial costs (Kadwa, 2018). The remaining profits are split between the millers and growers according to a division of proceeds agreement which exists between them. The growers receive 64.3647%, and the millers receive 35.6325% (Braude and Montmasson-Clair, 2019). The price per ton that a grower receives for their total deliveries to the mill during the season is calculated from the growers' proceeds (Kadwa, 2018). The millers receive their portion of the revenue from the millers' proceeds according to their share of the total sugar production. Diversified products like furfural that is produced by the Sezela mill are not included in the Sugar Act and the Sugar Industry Agreement. As such they are excluded from the division of proceeds calculations. Table 2.2 expands on the different milling companies and the notable products in their portfolios

Table 2.2: Product profile of the 6 South African sugar milling companies

South African Sugar Milling Companies: Operations and Products	
Tongaat Hulett Sugar Ltd (Tongaat Hulett, 2016)	<ul style="list-style-type: none"> – Retail white and brown sugar – Industrial sugars and sweeteners – Catering sugars and non-nutritive sugars – Electricity generation from bagasse for mill operations – Animal feed (Voermol Feeds)
RCL Foods Sugar & Milling (Pty) (SASA, 2019)	<ul style="list-style-type: none"> – 3 mills, 2 of the mills have refineries – A packaging plant – Sugar estates – Animal feed division – Cane and sugar transport
Gledhow Sugar Company (Pty) Ltd. (Gledhow Sugar Company, 2020)	<ul style="list-style-type: none"> – Refined white sugar – Bagasse is used for boiler fuel for operations and is sent to Sappi – Molasses is sent to a distillery
Umfolozi Sugar Mill (Pty) Ltd (Umfolozi Sugar Mill, 2016)	<ul style="list-style-type: none"> – Brown sugar – Electricity from bagasse for operations – Molasses is sent to NCP Alcohols
UCL Company (Pty) Ltd (UCL, 2018; SASA, 2019)	<ul style="list-style-type: none"> – VHP brown sugar and molasses – Wattle extract – Electricity from bagasse for operations – Operates a sugar mill, sawmill, wattle extract factory, a trading division, four farming estates, and a cane seed nursery
Illovo Sugar (Pty) Ltd (Illovo Sugar Africa, 2020)	<ul style="list-style-type: none"> – Industrial sugar – Refined and brown pre-packed sugar – Bulk raw sugar for refining, molasses, and syrup – Speciality sugars – Electricity is produced from bagasse to power operations – Sezela downstream: <ul style="list-style-type: none"> ○ Furfural, furfural alcohol, diacetyl, 2,3-pentanedione, natural methanol and agricultural nematicides – Merebank, Glendale and Tanzania ethanol distilleries: <ul style="list-style-type: none"> ○ Ethanol (potable extra neutral alcohol, 96%), anhydrous alcohol (99.9%), rectified extra neutral alcohol (96%), industrial alcohol (95%) and lactulose (Merebank distillery) – Ubombo Mill in Eswatini: <ul style="list-style-type: none"> ○ Electricity powers the mill operations and power is exported to the Eswatini grid according to an agreement with the Eswatini Electricity Company

There are concerns about how possible revenue from diversification routes would be shared between growers and millers, and a solution has not yet been proposed. However, numerous discussions were held (Braude and Montmasson-Clair, 2019). Whilst the sugar companies have embraced the concept of a sugarcane biorefinery, there are still considerable obstacles that need to be overcome before product diversification can become a reality. Two notable developments are the Biofuels Regulatory Framework and the South African Sugarcane Value Chain Master Plan to 2030, see Section 2.3.2.

2.3.2 SA government supporting diversification

2.3.2.1 Biofuels Regulatory Framework

The South African Biofuels Regulatory Framework and National Biofuels Feedstock Protocol (BFP) were published by the Department of Mineral Resources and Energy in February 2020. The Biofuels Regulatory Framework covered five aspects: Feedstock Protocol, mandatory blending regulations, cost recovery mechanism for blending biofuels, a Biofuels Subsidy Mechanism and selection criteria for biofuel projects requiring a subsidy (Department of Mineral Resources and Energy, 2020). As per the mandatory blending regulations, the Basic Fuel Price will be used as the biofuels transfer price. The feedstock protocol mentioned that the sugarcane equivalent of sucrose that would be otherwise exported could be diverted to biofuels production. According to Bole-Rentel and Chireshe (2020), the new framework would require clarification before it can inspire confidence in investors.

2.3.2.2 The South African Sugarcane Value Chain Master Plan to 2030

In 2020, the South African government put forth the South African Sugarcane Value Chain Master Plan to 2030 to aid in the sustainability of the sugar industry and the plan was signed on 16th November 2020. The sector was also exempted from specific clauses in the Competition Act, until June 2021, so that they may work together to implement the Sugar Master Plan (Department of Trade, Industry and Competition, 2020). Trade, Industry and Competition Minister Ebrahim Patel said: “The sugar master plan aims to diversify the value chain based on sugar cane away from one that is today almost solely focused on the production of raw and refined sugar, into one that in future produces a wider range of globally competitive sugarcane-based products.” (Villette, 2020).

Numerous short-term commitments were specified in the Sugar Master Plan to help restructure and stabilise the industry. These include:

- the active promotion and increased demand for locally produced sugar and its derivatives;
- the provision of trade protection from low priced and dumped imports while the sugar industry undergoes restructuring;
- the protection and preservation of jobs during the restructuring;
- the development of a detailed plan that will balance the industries capacity for market requirements, improve the efficiency of the entire supply chain and restore profitability as well as setting the foundation for a sustainable, competitive, and diversified sugarcane value chain (Anon., 2020).

Additionally, several task teams were established to focus on long-term strategies. One of these teams is the sugarcane-based value-chain diversification strategy. The objective of this task team is to investigate attractive opportunities in the local and international markets for sugarcane-based products and to provide recommendations for funding, regulatory frameworks, licensing requirements, infrastructure requirements, amendments to the Sugar Industry Agreements etc. that will help the sugar industry realise diversification (Anon., 2020).

An Executive Oversight Committee was established to ensure leadership and co-ordination during the Sugar Master Plan implementation. The committee is composed of members from the following sectors (Anon., 2020):

- **Retail and Industrial Users:** CEOs who are appointed by the minister, the Consumer Goods Council of South Africa (CGCSA), the Beverage Association of South Africa (BEVSA)
- **The Sugar Industry:** Industry CEOs appointed by the minister, the South African Sugar Association (SASA), the South African Sugar Millers' Association NPC (SASMA), the South African Cane Growers Association and the South African Farmers Development Association
- **Labour:** Representative Trade Unions
- **Government:** Minister of Trade, Industry and Competition, Minister of Agriculture, Land Reform and Rural Development, standing representatives from the Department of Trade Industry and Competition, Department of Agriculture, Land Reform and Rural Development, Department of Mineral, Resources and Energy, Department of Higher Education, Science and Innovation, Department of Health, the National Treasury, the Industrial Development Corporation, and the International Trade Administration Commission

The publication of the Biofuels Regulatory Framework and the South African Sugarcane Value Chain Master Plan to 2030 are important milestones on the road to a diversified South African Sugar Industry, involving the strategic collaboration of the numerous sectors along the value chain.

2.3.3 SA Sugar Industry challenges

The Sugar Industry Master Plan was developed to stabilise the South African Sugar Industry, which has experienced major challenges over the last few years. Some of these challenges have been that the sugar industry has largely not evolved from a single revenue stream, distorted global prices of sugar, the Health Promotion Levy, unsustainable SACU tariffs and increased tariff-free imports from Eswatini.

2.3.3.1 Single revenue streams

Brazil and Mauritius are good examples of industries that have experienced revenue growth and stability from multiple product streams. The South African Sugar Industry, however, still significantly relies on

sugar as its primary source of revenue (Wienese and Purchase, 2004; Braude and Montmasson-Clair, 2019). When a sugar mill has multiple product streams, the overall revenue of the mill is increased. There is also the added benefit of protection from fluctuations in the sugar price. The sugar industry has two potential routes, the use of well understood conventional technologies like bioethanol and cogeneration or the less understood, unconventional route, which is the focus of this work.

2.3.3.2 Distorted markets and trade

The revenue that is generated from the import and export sugar sales in a season is used to calculate the industrial revenue, which is divided between the sugar millers and growers. South African sugar regulations require surplus sugar to be sold on the world market, regardless of the market price. These interacting scenarios often result in the sugar industry exporting sugar at a loss. The sugar market is distorted, and with many sugar-producing countries receiving extensive support from their governments, the average world market price is often found to be lower than the cost of production (Kadwa, 2019). Usually, producers cannot handle such low prices even when they have tariff protection. If the industry could divert their surplus sugar to higher value biochemical products, it would be more beneficial than exporting the sugar at a loss.

2.3.3.3 The SACU tariff

South Africa is part of the Southern African Customs Union (SACU) and uses a variable tariff determined from a dollar-based reference price for raw sugar to deter imports. Eswatini, which is also a part of SACU, has tariff-free access to the South African market and has used that to export sugar to South Africa at prices that are below those of local producers (Anon., 2020). In the 2017/2018 season, the SACU tariff inadvertently allowed for a large number of dumped imports of sugar (Braude and Montmasson-Clair, 2019). With the imported sugar displacing the domestic sugar market, the Sugar Industry Agreement, which obliges the industry to export surplus sugar, further hurt the industry by forcing the surplus sugar to be sold at the low market price. For the industry to reduce its revenue loss, it requires 240 000 tonnes of sugar to be taken off the market (Braude and Montmasson-Clair, 2019). This is relevant as this surplus of sugar could be used for biochemical or biofuel production.

2.3.3.4 Health-related legislation

In 2018 the government introduced the Health Promotion levy or “sugar tax”. This tax resulted in a drop in domestic market sales, with companies like Coca-Cola reducing their sugar content by 20% across all brands (Ensor, 2019).

2.4 Concepts used in techno-economic assessments

It is important to find a way to compare the feasibility of different biorefinery scenarios, especially considering the multitude of products, processes and technologies that are possible. Techno-economic assessments are suitable for this purpose. A techno-economic evaluation is a methodology framework that typically employs process modelling, engineering design and economic assessment to analyse the financial performance of a process or product (Burk,2018). Economic indicators are generally used to assess economic performance. These indicators can include Net Present Value (NPV), payback periods, Internal Rate of Return (IRR), Fixed Capital Investment (FCI) and Total Production Costs (TPC). The NPV, IRR and payback periods are obtained through a Discounted Cash Flow (DCF) calculation. Numerous Techno-Economic Assessments have been compiled over the years on biorefineries. However, it has proven to be challenging to compare the results of the different assessments as multiple different approaches were used (Mandegari *et al.*, 2017). A complete evaluation of the feasibility of a biorefinery should consider the displacement of fossil fuels, renewability and sustainability, impact on the environment, preservation of biodiversity and social responsibilities together with the economic feasibility (Sacramento-Rivero *et al.*, 2016). Zetterholm *et al.* (2020) further stated that early-stage biorefinery concepts should include the financial performance of the complete supply chain while paying attention to the feedstock price and product markets.

2.4.1 Capital cost estimation

Engineering economic analysis texts put considerable focus on capital cost estimation techniques. Different approaches should be used for different stages in the design process. Table 2.3 was adapted from Hytonen and Stuart (2013), who compiled the different categories of process design from various engineering economic texts into one source. As the stages of the design process advance, the methods which get used require more information and more detailed assessments. However, the uncertainty of the results reduces. The earliest stage involves the rejection of infeasible biorefinery products. This is often done with a multi-criteria decision framework which employs indicators that represent the sustainability of a biorefinery. Rejection is based on the indicator scores, economic analysis is usually not done at this stage, as a precise estimation is not possible with the low level of information that is available. However, capital cost estimation methods do exist for the early stage of design and levels of uncertainty can be estimated for them. Nevertheless, an early-stage economic analysis does not require a precise estimation as the purpose is to reject unfeasible products so that time and resources can be applied in the more detailed stages of design to a smaller product portfolio. The work presented in this study focuses on preliminary screening estimation methods.

Table 2.3: Characteristics of design analysis and technoeconomic analysis for different levels in the design process (adapted from Hytonen and Stuart (2013))

Design Analysis Characteristics				Techno-economic Analysis Characteristics			
Name	Goal	Number of Product - Process Combinations	Technology Development	Analysis Basis	CAPEX & OPEX	CAPEX & OPEX Ranges	Profitability Analysis
1) Process Creation	Systematic generation of alternatives, screening of unpromising alternatives, defining production capacity	Many combinations	Laboratory – Commercial	Input-Output process Mass & energy balance	Capacity factored, parametric models	Order of Magnitude	Operating profit, capital cost, gross profit, technological maturity
2) Concept Demonstration	See (1) above	Many combinations	Laboratory – Commercial	See (1) above	See (1) above	Order of Magnitude	See (1) above
3) Prefeasibility	Screening/ selection of alternatives and production capacity	Few (Fixed product, process, feedstock, capacity)	Pilot – Commercial	List of main process equipment. Input-output process mass & energy balance	Equipment factored, Parametric models	CAPEX: -30 – +50% OPEX: ± 20%	ROI, IRR
4) Feasibility	Screening of internal process options and technological solutions	Few (With many internal alternatives for technological solutions)	Demonstration – Commercial	Engineering & design data: main PFDs & equipment listing, detailed mass & energy balance	See (3) above	CAPEX: -20 – +30% OPEX: ± 10%	ROI, IRR
5) Engineering for Definition	Budget authorization/ cost control	Few	Demonstration – Commercial	Engineering & design data: PFDs, P&IDs, utility flow drawings, equipment data sheets, motor lists, electrical diagrams, piping isometrics, equipment & piping layout drawings, plot plans & engineering specifications	Semi detailed unit-cost estimation with assembly-level line items	CAPEX: -15 – +20% OPEX: ± 10%	ROI, IRR
6) Detailed Engineering	Control of bid/ tender	One	Demonstration – Commercial	See (5) above	Detailed unit-cost estimation with detailed Take off	CAPEX: -10 – +15% OPEX: ± 10%	ROI, IRR

2.4.2 Preliminary screening cost estimation methods

Different capital cost estimation methods can be used in the early stages of biorefinery evaluations, and they depend on the available information. Three categories of estimations are possible in the preliminary screening phase (Tsagkari *et al.*, 2016).

Exponent estimates require data from historically similar plants and estimate the cost of the new plant by taking a ratio of the capacities and raising the ratio by an exponent. Early-stage techno-economic analysis often relies on publicly available information (Hytonen and Stuart, 2013). In the early stages of technology development, the developers tend to make information public to attract funding for further development. Information gets less transparent as the technology gets closer to commercialisation (Hytonen and Stuart, 2013). With this in mind, it is essential to critically analyse the data that gets used in the capacity factor method as there may be significant discrepancies between initial estimates as provided by the developer, in their initial design stage, and final estimates after commercialisation.

Factorial estimates require a list of the equipment needed for the plant along with costs of the equipment. The theory is that the capital cost of a plant can be correlated to the cost of the purchased equipment. Lang (1947) introduced this method by stating that the equipment cost when multiplied by a factor that is related to the process type (solid, fluid, solid-fluid), would provide the cost estimate of the plant. (Tsagkari *et al.*, 2016).

Functional Unit estimates or the step counting method, correlates the capital cost of a process to fundamental process parameters, plant capacity, number of significant process steps, pressure, temperature, materials of construction etc. The American Association of Cost Engineers defines a functional unit or significant processing step as the equipment (including auxiliaries) that are required to complete an operation in the process. Numerous authors developed correlations between the capital costs and process parameters and each author provided their methods and definitions for the functional units and the required processing parameters that were associated with them (Tsagkari *et al.*, 2016).

2.4.3 Operational cost estimations

The Operational Expenditure (OPEX) together with the Capital Expenditure (CAPEX) is required for an economic assessment. The OPEX includes Fixed Production Costs (FPC), Variable Production Costs (VPC) and General Expenses (GE). The VPC is dependent on the capacity of the plant, and it includes raw material cost, utility costs, consumables, and waste management. The VPC requires a mass and energy balance. However, factors can be used in their place if the

mass and energy balance is not available (Peters *et al.*, 2003). The FPC is not dependent on the production capacity, and it includes maintenance, capital charges, insurance, local taxes, operating labour, laboratory costs, supervision, and plant overheads. These fixed costs can be obtained by applying factors to the Fixed Capital Investment (FCI) or operating labour. The operating labour, on the other hand, is often calculated based on the salaries paid to equipment operators in an area (Peters *et al.*, 2003).

The detailed engineering stage in a design process has the most accurate capital and operating cost estimates as they use more detailed calculations with complete mass and energy balances, known equipment specifications, piping and instrumentation, installation costs and labour rates.

Hytonen and Stuart (2013) stated that even though accuracy is lost during the early stages of design, the simplifications can be justified when multiple processes and products are required to be analysed in a limited time. They further specified that relatively correct results could be obtained if the uncertainties which result from the simple methods are investigated systematically.

2.4.4 Uncertainties in decision-making

Uncertainty and complexity are often associated with the decision-making process. When a biorefinery is considered with many different potential products and processing routes, the complexity of the decision increases. Additionally, the successful implementation of a biorefinery requires the consideration of feedstock costs, product prices and market potential, displacement of fossil fuels, impact on the environment, social responsibility, to name a few, all of which are inherently uncertain. The addition of a decision-making tool can offer support by limiting the number of possibilities and rejecting non-promising strategies, which in turn reduces the uncertainty and complexity of the decision-making process (Sanaei, 2014). It should be noted that different companies have different objectives, and whilst one company might prefer a product that would penetrate the green market, another company that has limited financial resources would select a product which would suit their capital investment criteria. Essentially, decisions should be made in line with the company's vision and not on the choices made by other companies (Sanaei, 2014).

Various sources of uncertainty exist when selecting a biorefinery project. These can be classified as model-inherent, process-inherent, external, and discrete (Pistikopoulos, 1995). Process inherent uncertainties deal directly with the process. For example, biomass conversions, equipment selections and the required operators, required input values for energy consumption

calculations or process integration setups. Model-inherent uncertainties refer to uncertainties with the model itself (Hytonen and Stuart, 2013). External uncertainties refer to uncertainties in product prices and feedstock costs (Hytonen and Stuart, 2013). Discrete uncertainties refer to aspects like the availability of technology, effects of government intervention or availability of financing, and they should be included in the pre-screening stages (Hytonen and Stuart, 2013). Discrete uncertainties which have an unknown value, time frame or existence should be considered as they often impact on the process-inherent, model-inherent, and external uncertainties (Hytonen and Stuart, 2013). Examples of the different sources of uncertainty as per their grouping of process-inherent, model-inherent, external, and discrete were found in literature.

2.4.4.1 Process-inherent uncertainty

Process integration is inherent in the definition of a biorefinery. However, in the early stages of design, the information on the degree of integration that is possible is usually unknown. Some of the critical components of integration could include shared heat and power systems between different product sections of the biorefinery. If an existing facility is to be expanded through the addition of new biorefinery products, then the integration will have an impact on the production costs of the existing products (Hytonen and Stuart, 2013).

If the overall energy balance is unavailable, then energy integration would not be possible, and uncertainty would be present. Operating labour would be shared in the integrated process, operating labour costs and plant overheads would be reduced in the production costs of the existing process. By sharing the administration, research and development and marketing costs in the integrated process, the general expenses would reduce the total production costs calculation (Hytonen and Stuart, 2013).

2.4.4.2 Model-inherent uncertainty

An uncertainty would be present if a new process were to use the capacity scaling method with a capacity exponent of 0.67 to obtain the capital expenditure. The capacity scaling value is inherently uncertain as it is by definition, an average. Cheali *et al.* (2015) conducted a study on the uncertainties which are present in preliminary cost estimation methods of Class 5 (Order-of-magnitude) and Class 4 (Factor) estimates by assessing different biorefinery processes. They found that the Class estimation methods produced different results and concluded that a probabilistic approach, which accounts for uncertainties, should be considered when using Class 4 and 5 cost estimates rather than a deterministic approach. Cheali *et al.* (2015) further stated that their study supported the argument that capital and operating expenditure estimates are useful for comparing and screening process and product alternatives in the early stages of design.

Additionally, these authors suggested that if reasonable assumptions are made, unfeasible products, as determined by an early-stage cost estimation method should be removed from subsequent decision-making phases (Cheali *et al.*, 2015).

If a conflict exists when the NPV and IRR are used to rank projects, then the uncertainty in the ranking would exist if they are analysed incorrectly. A conflict occurs when comparing projects, and the NPV of one project is high, whilst the IRR of the other project is higher than the first. The preferred method is to accept the project with the higher NPV (Berk *et al.*, 2015). This is because the IRR assumes that any cash flow can be reinvested at the return rate. However, there is no guarantee that an opportunity for reinvestment will occur (Berk *et al.*, 2015). Additionally, the NPV is an absolute measure, whilst the IRR is a relative measure. When the NPV is used, it is clear which project would generate the most value, in monetary terms, for the company, this is, however, not clear when the IRR is used (Berk *et al.*, 2015). The NPV is dependent on the project size, and a project might be selected because it has the higher NPV. However multiple smaller investments could generate a higher overall NPV for an equivalent investment as the larger project. Additionally, for example, a large-scale biofuel plant with a high NPV could be compared to a low-volume side stream product with a high IRR. The low-volume side stream product could be rejected. However, it might perform better than other similarly scaled processes (Hytonen and Stuart, 2013). It would be beneficial to rank and compare projects of similar scales before altogether rejecting a project.

2.4.4.3 External uncertainty

If a large-scale biorefinery is implemented, the feedstock price is expected to increase since the demand for the feedstock, with limited availability, increases. This increased demand would cause a surge in competition and reallocation of other feedstock in the market (Zetterholm *et al.*, 2020). Considerations on the choice of the feedstock and the assumptions that are made surrounding it should be as realistic as possible as underestimating the value or abundance of the feedstock could drastically skew the performance of the biorefinery (Zetterholm *et al.*, 2020).

It has been identified that in a biomass project, economic risks are not only attributed to the supply side but are also associated with variability in the product market price and the presence of competing commodities (Wang, 2014). To demonstrate the impact that the volatility in market prices and variability of biomass costs has on the economic performance of a biorefinery, Wang (2014) investigated the production of cellulosic sugar from corn stover. He concluded that whilst biomass supply security is crucial fluctuating product prices posed a significant risk to the biorefinery's success. Wang (2014) suggested that an agreement of a stable price with a long-

term buyer and the support of local communities, government and industry would mitigate the risk.

2.4.4.4 Discrete uncertainty

If capital investment limits a company, then they should investigate whether financing is possible in the preliminary phase of the decision-making process. If a technology included in a process becomes shelved by the technology provider, then alternatives would need to be investigated. Technology uncertainties are higher for newer biobased systems as the maturity level is low, and the technology may not be well understood (Balaman, 2018).

It might be uncertain whether the government will provide support in the form of funding. In these cases, scenarios which include or exclude subsidies on the product price or regulations on feedstock costs should be considered. Additionally, the government may provide extra subsidies if a plant is located in a particular area. The location of the biorefinery should be considered in this respect as well (Balaman, 2018).

2.4.4.5 Methods to account for uncertainty

Numerous sources of uncertainty exist when performing a techno-economic assessment as described in sections 2.4.4.1 to 2.4.4.4. It is important to identify and quantify the different sources of uncertainty that exist in a project. Furthermore, the uncertainty should be incorporated when determining which products or processes are feasible or unfeasible. With regards to the examples presented in sections 2.4.4.1 to 2.4.4.4, the following uncertainties would need to be accounted for (Hytonen and Stuart, 2013):

- The effect of not including energy integration can be accounted for by analysing the utility cost in the total production cost calculation.
- The consequence of reduced operating labour, plant overheads and general expenses, due to process integration, can be accounted for in the total production cost calculation.
- The capacity-scaling constant used in order-of-magnitude calculations should be analysed.
- The effects of using preliminary cost estimation methods for Class 4 and 5 cost estimates can be used provided the uncertainties are accounted for with a probabilistic approach.
- In the case that uncertainty exists because of the occurrence of conflicting results when ranking projects based on the project NPV and IRR, the projects should be ranked according to their similarities like the project size. All uncertainties should be addressed before a project is rejected.

- Uncertainties surrounding the biomass costs and volatile product market prices should be considered.
- The effects of additional financing or possible government subsidies should be investigated as well as the possibility of process technologies becoming obsolete as newer technologies are developed for biorefinery processes.

Techno-economic analysis often incorporates either a quantitative or qualitative method to address the uncertainties. An example of a qualitative method is the SWOT (strengths, weaknesses, opportunities, and threats) analysis approach. Quantitative methods are divided into deterministic and stochastic methods. A further optimisation method incorporates a wide range of strategies which include either stochastic or deterministic methods.

The simplest form of a deterministic method to evaluate uncertainty is the sensitivity analysis which provides a range of values to represent the uncertain parameter. A maximum and minimum amount can be used to describe the best and worst cases. Additionally, one parameter can be varied at a time while keeping other variables constant. This would identify the different effects that each parameter has on the entire system (Balaman, 2018). Other deterministic methods include scenario analysis, scoring methods and discounting methods.

- The scenario analysis method makes use of sensitivity analysis principles. The process design group can define scenarios as the most likely future outcomes. These scenarios can then be examined and analysed.
- The scoring method is a version of the sensitivity or scenario analysis. The scoring method makes use of an ordinal scale to quantify the uncertainty. Understanding of the system is used to quantify uncertainties rather than applying changes to a techno-economic model.
- The discounting method is a version of the scoring method that takes a qualitative approach to the scoring method. For example, suppose the technology that is used in the process is mature. In that case, the profitability is not discounted whilst if the technology is not mature and is uncertain, then the profitability of the process is discounted according to some pre-specified scale (Hytonen and Stuart, 2013).
- Stochastic methods assign a probability distribution to the uncertain parameters, and the most well-known example is the Monte Carlo analysis (Hytonen and Stuart, 2013).
- Optimisation methods minimise an objective function by adjusting scenarios, with the optimal scenario identified as the one that yields the lowest value for the objective function.

Table 2.4 (adapted from Hytonen and Stuart, 2013) shows the types of uncertainties that are present in the early stages of process design.

Table 2.4: Types of uncertainties and the analysis methods that can be employed to quantify them, adapted from Hytonen and Stuart (2013)

Uncertainty	Process Creation		Concept demonstration	
	Examples	Analysis Methods	Examples	Analysis Methods
Model-Inherent	Cost-estimation models, M&E balance dependencies	Scenario analysis, sensitivity analysis, scoring methods	Cost-estimation models	Discounting methods
Process-Inherent	Product yields, energy consumption, equipment costs, process development scale	-	Process integration impacts, cost of all required equipment, consumption of all raw materials	Scenario analysis, sensitivity analysis, stochastic analysis
External	Raw material cost, product prices, market demand	-	Feedstock price, product price, forecasts of prices	-
Discrete	Availability of overall process technology, financing, and subsidies	-	Availability of technological solution and equipment for specific process steps, magnitude, and duration of subsidies	Scenario analysis

2.4.5 Uncertainty case study: Lysine HCl

The lysine industry has had instances of price-fixing, conspiracies, and cartels. Connor (2007) provided a detailed explanation of the events that unfolded between ADM, Ajinomoto, Kyowa, Sewon and Cheil, the five conspirators in the lysine cartel. Between 1960 and 1990, Asian companies dominated the lysine markets with Ajinomoto controlling over 60% of the global markets. During these years there were numerous cases of price-fixing and the companies would limit each other's exports of lysine to countries where they had a plant in operation.

Major global market shifts occurred when the American company ADM entered the lysine market. In the 1990s, ADM doubled its capacity over Ajinomoto, and their aggressive tactics caused Ajinomoto and Kyowa's market shares to drop drastically. A price war existed between 1991 and 1992, ADM essentially went from 0% to 71% control of the US lysine market by underpricing their competitors. ADM note that they would oversupply the US markets and started to export their lysine, which caused the world lysine price to be drastically reduced (Connor, 2007).

In 1992, ADM was experiencing difficulties with contamination of their lysine fermenters which resulted in them losing millions when they had to discard bad batches of lysine. Further and probably more significant, was that ADM had reduced the market price of lysine by so much, that they were now producing lysine at a loss. In 1992, ADM, Ajinomoto, Kyowa, Sewon and Cheil

formed the lysine cartel. These five members controlled about 97% of the world lysine market. In the 1990s, the cartel limited the entry of new players onto the market, Cargill was the only company during this time to construct a plant in the US (Connor, 2007).

The cartel further ignored the construction of two plants, as they regarded their capacities as insignificant. The cartel did not ignore the third instance of a new company entering the lysine market. This happened in 1995 by a company called AECl who built a 10 800-tonne lysine facility in Umbogintwini, South Africa. During a meeting where the cartel discussed how they would distribute the global volume between the five members, they acknowledged AECl and adjusted their calculations (Connor, 2007). The lysine conspiracy concluded in 1997 as ADM was subpoenaed for their activities in the lysine industry by the US government. Management in ADM was simultaneously charged with being involved in price-fixing of the citric acid markets (Connor, 2007).

The lysine facility in South Africa stopped production more than a decade after the lysine cartel was disbanded. The reason that AECl, which was later known as SA Bioproducts, eventually exited the lysine market was because of impacts caused by the feedstock price rather than the product selling price or market share. SA Bioproducts used high test molasses (HTM) and corn steep liquor (ITAC, 2006) as the feed material for their production of lysine HCl. The HTM was obtained at beneficial prices from a sugar producer that was situated near the lysine plant. Following the non-renewal of the supply contract between SASA and SA Bioproducts, the company terminated production in 2011 (ITAC, 2011). SASA's new pricing structure would have caused SA Bioproducts to produce lysine HCl at a loss due to the increased domestic feedstock (ITAC, 2011).

This was not the only issue that the lysine plant experienced during its lifetime. Prior to its termination, numerous reports were filed to the International Trade Administration Commission (ITAC) of South Africa for protection from increased imports and dumping of lysine on the South African markets (see ITAC Reports Nos. 171, 193, 199, 248, and 372.) Safeguards that were implemented can be found in ITAC Reports Nos. 237, 250, 286, 340 and 380.

SA Bioproducts were being severely undercut by lysine, in the form of Biolys, that was imported from the US and other countries. Biolys had a lysine content of 50.7% whilst the lysine HCl that was manufactured by SA Bioproducts had a lysine content of 78.8%. In 2001, 1 500 t of lysine HCl was imported to South Africa from the US. Following an anti-dumping duty that was implemented in 2002, the imports from the US were reduced to 14 kg (ITAC, 2006). Biolys was

instead imported from 2002 onwards following the anti-dumping duty of lysine HCl. In 2007, safeguard duties were implemented against the increase of lysine imports from all countries except developing countries (ITAC, 2007). In 2010, ITAC recommended an increase in the rate of duty from free of duty to 10% for lysine and similar feed supplements (ITAC, 2010). In 2011, ITAC reduced the rate of duty back to free of duty and eventually terminated the anti-dumping duties on lysine as SA Bioproducts stopped production (ITAC, 2011).

If the key model parameters of a project can be identified, and a reasonable estimate of these parameter ranges can be obtained, then the vulnerability of the project can be assessed. The lysine case illustrated the importance of the production volume relative to world market size, the number of players in the market and the sensitivity of the project feasibility to variations in feedstock and product market prices.

2.5 Preliminary methods to assess the feasibility of a biorefinery

Numerous approaches have been taken to assess the feasibility of different biorefinery processes. Some of these techniques were the early-stage sustainability method which made use of indicators to perform product comparisons, optimisation with the use of superstructures for optimum technology and/or configuration selection, and conceptual designs which used commercial software (de Assis, 2019). Optimisation and conceptual designs are methods that are used in the early project stages. However, they often require detailed input information, complex calculations, and specialised software. Tools which make use of these methods should be simple and straightforward to be used as early-stage assessment tools.

2.5.1 Early-stage sustainability assessment method

The early-stage sustainability assessment method was found in numerous studies for the preliminary assessment of biorefinery products. This method typically employs indicators to represent the environmental sustainability as well as social and economic impacts of a biorefinery. The indicators are weighted and combined into one index, which is then used to compare different biorefinery products (Patel, 2013; Posada *et al.*, 2013; Moncada *et al.*, 2015). Variations of this approach have been used where authors create their own versions of the indicators. Common indicators were found to be (Moncada *et al.*, 2015):

- the economic constraint (EC), which relates the cost of the raw material to the marketable products,

- the environmental impact of raw materials (EI), which represents greenhouse gas emissions and cumulative energy demand, process costs,
- the environmental impact (PCEI), which describes potential technological challenges,
- the environmental-health-safety index (EHSI), which is used to represent any hazards related to the process, and
- the risk aspect (RA), which considers economic and technical factors that are external to the process (Moncada *et al.*, 2015).

According to Patel (2013), the following information is required to use this method:

- Chemical reaction data derived from laboratory results
- Cumulative energy demand and greenhouse gas emissions for raw materials
- Physiochemical properties
- Prices of the raw materials, products, and co-products
- Chemical hazards information

Posada *et al.* (2013) used this method to screen bioethanol derivatives, Patel (2013) assessed levoglucosan from wheat straw, 1,3-butadiene from ethanol, 2-ethylhexanol from ethanol and other biobased products. Moncada *et al.* (2015) considered syngas derivatives by catalytic conversion, carbohydrate derivatives by biochemical conversion, and glycerol derivatives from both catalytic and biochemical transformations.

The New Products Greenhouse (NPG) Toolbox was developed by the Sugar Milling Research Institute NPC, as a first pass screening tool to assess the feasibility of new products for the South African sugarcane industry. The tool considers feedstock competition, technology, economic and market constraints. The built-in algorithms return an economic constraint, business risk score and a technology risk score for the products that are assessed. These scores can then be used to rank the products. The NPG toolbox does not include capital and operating expenditure. (Booyesen *et al.*, 2017)

2.5.2 Optimisation with superstructures

Numerous studies and tools were created with the optimisation of superstructure methods. Studies on sugarcane biorefineries include:

- Mutenure *et al.* (2018) optimised the supply chain network to obtain sugar and bioethanol from sugarcane in South Africa.

- Costa *et al.* (2016) optimised the process and environmental route to get bioethanol, electricity, and vinasse from sugarcane in Brazil.
- Albarelli *et al.* (2017) maximised the energy efficiency and minimised the investment cost to obtain the optimum ethanol-methanol configuration for a sugarcane biorefinery.
- Martínez-Guido *et al.* (2016) found the optimal configuration needed to convert a Mexican sugar mill into an integrated biorefinery producing sugar and bioethanol. They included an environmental and social analysis.

The optimisation methods assess different optimisation objectives, including minimising costs, wastes, or environmental impacts, or maximising yield or profit. Cheali *et al.* (2016) provided a comprehensive six-step description of the optimisation methods, which was summarised as:

1. Problem definition

The scope of the biorefinery is defined. The objective function is defined (maximise profit, minimise production costs, etc.), and the optimisation scenario is selected.

2. Superstructure definition

A superstructure consists of all the processing blocks that are used to obtain a final product from the raw material. In the superstructure definition step, a literature review is conducted, and a processing block defines each processing step in the biorefinery. A processing block can consist of one or many unit operations. A generic model is incorporated in each processing block to represent tasks like reactions, mixing, waste separation and product separation.

3. Data collection and modelling

Simple input-output mass balances define the generic models in the processing blocks. The data that are required for each processing block mass balance must be collected. A ratio to the mass inlet flow is applied to obtain the chemicals and utilities used in a process block. Reactions are calculated with stoichiometry and conversion fractions. Removal fractions are used to obtain waste streams, and product separation fractions are used to obtain the product outlet streams. The data required for each processing block in the defined superstructure can be collected from technical reports, experimental data, simulation results or design flowsheet stream tables.

4. Models and data verification

Equations and constraints for each processing block are formulated, and the model is solved. The results are then verified against the simulation results from the literature data.

5. Formulation and solution of the optimisation problem

The optimisation problem is formulated based on the objective function and constraints as either a Mixed Integer Linear Programming (MILP) problem or a Mixed Integer Non-Linear Programming problem. The output of the model is the most optimal biorefinery configuration.

6. A sustainability analysis concerning resources consumption and environmental impact

Indicators or tools are incorporated into the framework. If the environmental assessment is negative, then constraints are relaxed until a positive solution is found.

The environmental assessments can be obtained with impact categorisation algorithms like the WASTE Reduction (WAR) algorithm and the Gauging Reaction Effectiveness for the Environmental Sustainability of Chemistries with a Multi-objective Process Evaluator (GREENSCOPE) (Aristizabal-Marulanda and Alzate, 2018). WAR determines the potential environmental impact, which measures the average unrealised effect or effects that mass and energy emissions would have on the environment (Aristizabal-Marulanda and Alzate, 2018). GREENSCOPE quantifies process sustainability and generates a life cycle inventory. Life Cycle Assessments tools can also be included to quantify the environmental impact (Aristizabal-Marulanda and Alzate, 2018).

Studies which used the optimisation of superstructures include Kelloway and Daotidis (2014) who used MATLAB to obtain mass and energy balances. Kokossis *et al.* (2010) used GAMS and a database of material flow, stream conditions and capital and operating costs which was linked to Microsoft Excel (Tsakalova *et al.*, 2011). Both Kokossis *et al.* (2010) and Kelloway and Daotidis (2014) used correlations to obtain capital costs.

2.5.3 Conceptual process designs

The conceptual design stage of a biorefinery includes a technical, economic, and environmental analysis. The generation of mass and energy balances to obtain the technical analysis often employs commercial software packages like Aspen Plus, CHEMCAD, Pro II and HYSYS. Aspen can do the economic analysis with the use of the Process Economic Analyzer, and algorithms like the United States Environmental Protection Agency (US-EPA) Waste Reduction (WAR) and GREENSCOPE or Life Cycle Assessment (LCA) studies provide the environmental analysis (Aristizabal-Marulanda and Cardona Alzate, 2018). Published experimental data, including reaction kinetics, yields, operational conditions, and feedstock characteristics, are often used as inputs to the simulation packages. The best performing scenarios from the simulation tools can be compared to assess which biorefinery performs better against pre-specified performance

criteria. There are numerous simulation-based studies of sugarcane biorefineries in literature (Chikava, 2018; Pachón *et al.*, 2020).

2.5.4 Studies that incorporate preliminary cost estimation methods

Claypool (2011) developed a spreadsheet-based model called the Biorenewables Process Evaluation Tool (BioPET). The model includes fermentation, adsorption, crystallisation, distillation, liquid-liquid extraction and catalysis, and mass balances were performed for each unit operation. The capital costs were obtained with the exponential estimate method. Sensitivity analysis in the form of Monte Carlo simulations was integrated into the model as well. BioPET estimates the minimum selling price required for the process (Claypool, 2011). Viswanathan (2015) made improvements to the BioPET model and renamed it the Early-Stage Techno-Economic Analysis (ESTEAs).

Torres (2016) conducted an economic risk analysis with Monte Carlo simulations to assess three aspects: Firstly, the feasibility of integrating a biobutanol facility to an existing sugar mill, secondly, the risk of using a process with limited information by evaluating the integration of a muconic acid facility to the sugar mill, and thirdly, the potential of using lignocellulosic technologies to produce sugar. Process information was obtained from literature, and simple mass and energy balances were calculated in an Excel spreadsheet. Torres used the Taylor step scoring method (functional unit method) to obtain capital estimations. The results from the mass and energy balances were used to get the variable costs while using factors for the fixed production costs. The NPV, IRR and payback periods were obtained using a Discounted Cash Flow Analysis. The main focus of Torres's (2016) work was risk analysis. A sensitivity analysis was conducted producing tornado plots. Additionally, the @Risk software, which integrates with the Microsoft Excel spreadsheet, was used to perform Monte Carlo simulations.

Tsagkari *et al.* (2020) proposed a new method to specifically address the need for a shortcut cost estimation method for biorefinery processes which would be suitable for Class 5 cost estimates, of TRL 2-3 and uncertainties ranging from -50% to +100%. The proposed method follows a 'Process Block Build-Up' route. A modular approach was followed whereby each process block constitutes either a chemical, physical, or auxiliary unit operation. Each process block has its own cost power function. Two techniques were employed, the detailed cost estimate and power law (order-of-magnitude) approach. The capital cost was calculated as the sum of each process block cost. Each process block had an efficiency associated with it that contributes to the cost. A

fermentation process block would have productivity whilst a chemical reaction block would have a yield as the efficiency.

Additionally, the method incorporates an uncertainty model. This model was required because the method relies on historical cost information and biorefinery processes with low technology readiness levels. The cost function of each process block made use of reference capacities and costs, efficiencies, cost-capacity exponents, and the output capacity. A database of 331 large-scale global commercial biorefineries was included in the model to be used as the reference information for the cost functions (Tsagkari *et al.*, 2020).

2.6 Purpose of this study

Diversification of sugar to produce high-value products instead of exporting the sugar at low market prices could improve the long-term sustainability of the South African Sugar Industry. If this is done, then the losses that currently incurs from exporting sugar would be reduced. With the implementation of the Sugar Industry Master Plan, the industry is preparing to assess the different products and processes that would be feasible and bring about sustainability in the sugar industry. The problem lies in deciding which bioproduct candidates should get investigated first. The Sugar Master Plan suggested that attention should be paid to bioethanol for fuel blending, bio-jet fuel, potable, industrial and pharmaceutical-grade bioethanol, cogeneration, biogas, low-calorie sweeteners, platform and speciality chemicals, and biopolymers (Anon., 2020). Additionally, the industry will need to decide on whether a few products will be produced industry-wide, or if specific companies or milling areas will decide which products to produce according to their existing product portfolios.

Numerous techno-economic studies have been performed in recent years. However, their results are static. It is believed that a tool should be created so that it can accommodate the changing economic environment that surrounds biofuels, biochemicals and cogeneration. It should also be able to adjust to the constant fluctuations in the market prices due to the uptake of biobased products. If this tool is created, then the potential products from biomass can be assessed timeously, reducing the number of products that should be considered for a more detailed design.

The NPG toolbox (Booyesen *et al.*, 2017) already exists for high-level (early-stage) elimination of products that would be unfeasible. However, it cannot be used to reliably predict the economic feasibility of products as it lacks estimates for capital and operational expenditure. On the other hand, detailed techno-economic models at the preliminary design stage, such as those built using

Aspen or MATLAB, provide a lower uncertainty on the technology and production costs (Mandegari *et al.*, 2017; Pachón *et al.*, 2020). Numerous studies have already been performed on some diversification products from bagasse in South Africa (Petersen *et al.*, 2014; Farzad *et al.*, 2017; Petersen *et al.*, 2017; Nieder-Heitmann *et al.*, 2019). However, when a large number of potential diversification candidates require screening, the resource cost of building detailed mass and energy balances for each option would be significant. Hence the preliminary cost estimation technique was selected for this work.

The development of an intermediate tool as an interface between early-stage sustainability assessments and detailed preliminary design was thought to be beneficial to overcome their respective limitations. Numerous tools and methods have been created that require a higher level of detailed information, as reviewed above. Whilst factorial and functional cost estimation methods have been developed, the approach of Tsagkari *et al.* (2020) using exponential estimates for CAPEX calculations as information on biorefineries was deemed more suitable.

The following chapters contain the two publications emanating from this research. The first publication in chapter 3 describes the method incorporated in S-BEAT and gives five case studies for potential biorefinery products for the South African Sugar Industry are presented. It further discusses the pros and cons of S-BEAT. The second publication in chapter 4 presents further developments of the toolbox, whereby the effect of using different mill streams on economic performance is considered. Furthermore, several additional products were assessed. The economics of various products produced from either the same or different mill streams are compared, and an overall summary of the product profitability is given. Additionally, a discussion of the differences between the results of papers 1 and 2 were included at the end of chapter 4. Due to the limited space for detail available in publications, chapter 5 defines the assumptions, limitations, decisions, and discussions surrounding the development of S-BEAT. Additional features of S-BEAT not described in the publications, in particular the minimum selling price seeker, are introduced as well, and a user manual is provided in Appendix B.

2.7 References

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CHAPTER 3: PAPER I

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

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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 $\pm 30\%$ to $\pm 50\%$, 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 (Booyesen *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 $\pm 30\%$ (Sinnot, 2005) to $\pm 50\%$ (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 Guest¹. 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 (Sinnott, 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.

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

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:

$$FCI_{New} = FCI_{New}^* + 0.05FCI_{New}^* \quad (2)$$

$$WC = 0.1FCI_{New} \quad (3)$$

$$TCI = FCI_{New} + WC \quad (4)$$

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 <i>Raw Materials</i>
Miscellaneous Materials	10%	of Maintenance ^a
Utilities	15%	of TPC ^b . See <i>Utilities</i>
Waste Management	5%	of TPC
Fixed Production Costs		
Maintenance	5%	of FCI ^a
Capital Charges	10%	
Insurance	1%	
Local Tax	2%	
Operating Labour	-	See <i>Operating Labour and Salaries</i>
Salaries	-	See <i>Operating Labour and Salaries</i>
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 cane² 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

²Research – 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' salary³ result in the operating labour.

The salaries of a plant manager, process engineer, admin clerk and secretary⁴ 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

³Payscale.com, https://www.payscale.com/research/ZA/Job=Chemical_Process_Operator/Salary, last accessed on 11 May 2017

⁴Payscale.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 ⁹	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 recycling⁷ (LyondellBasell Industries Holdings BV, 2017). A simplified process scheme was then obtained from Daftaribesheli (2009).

⁶Ethylene Manufacturing Technology Description, <https://www.intratec.us/free-tools/how-to-make/ethylene-manufacture-technology>, last accessed on 11 August 2017

⁷LyondellBasell 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's⁸ 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 Solutions⁸ (2017), are further described below.

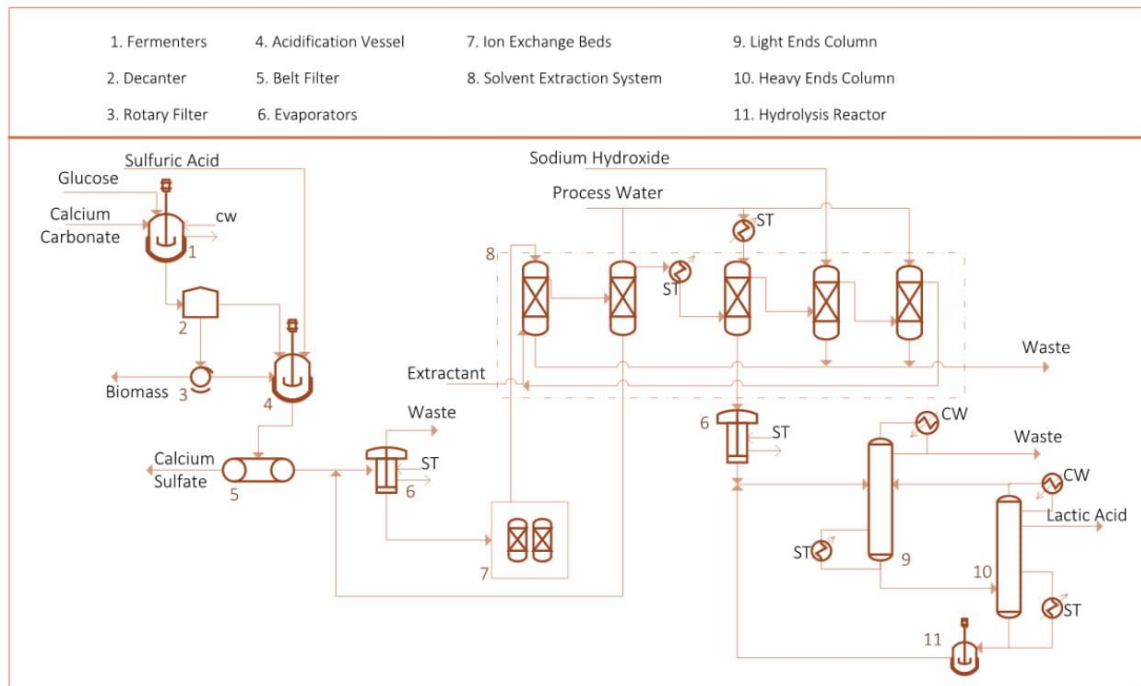


Figure 1. Lactic Acid process flow diagram adapted from Intratec Solutions (2017)⁸.

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.

⁸Lactic 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 633⁴ (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 ⁹	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

⁹ (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 representatives⁹ 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×10 ⁶)	NPV (R×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.

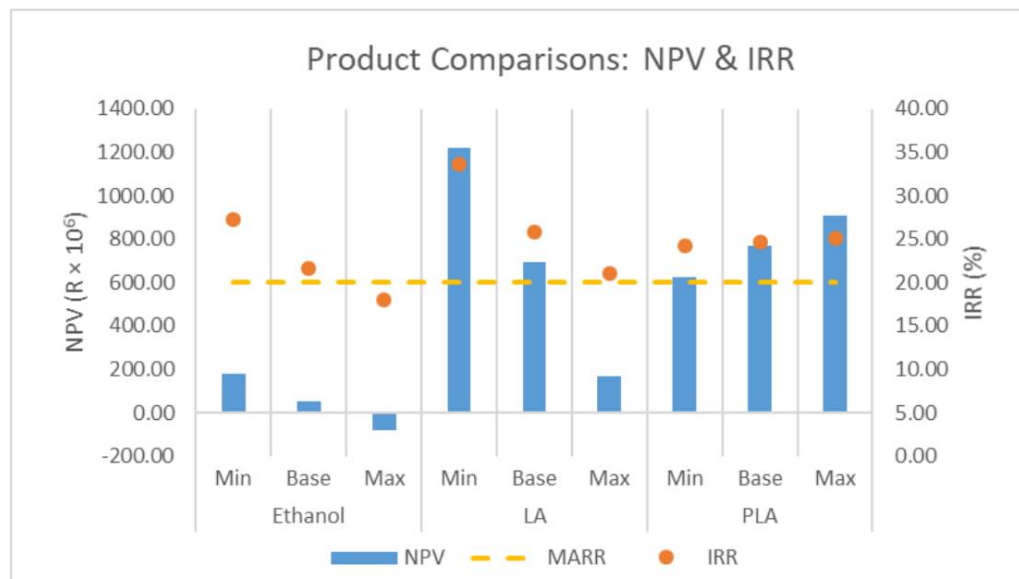


Figure 2. Economic indicators for the minimum, maximum and base cases for ethanol, lactic acid and polylactic acid.

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.

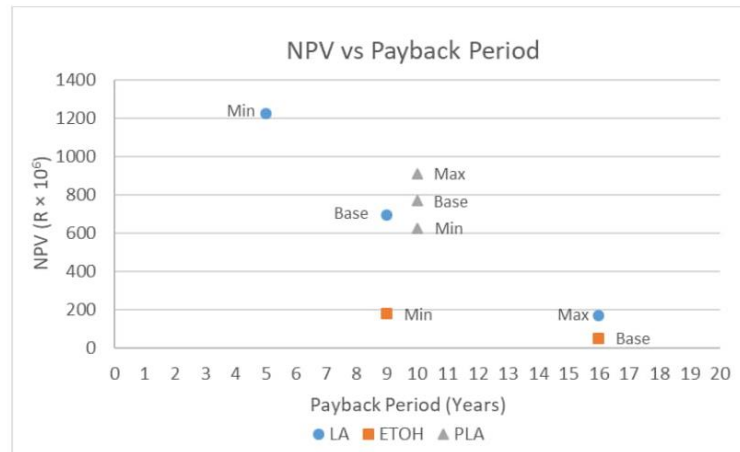


Figure 3. Net present value and payback period for the minimum, maximum and base cases for ethanol, lactic acid and polylactic acid.

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.

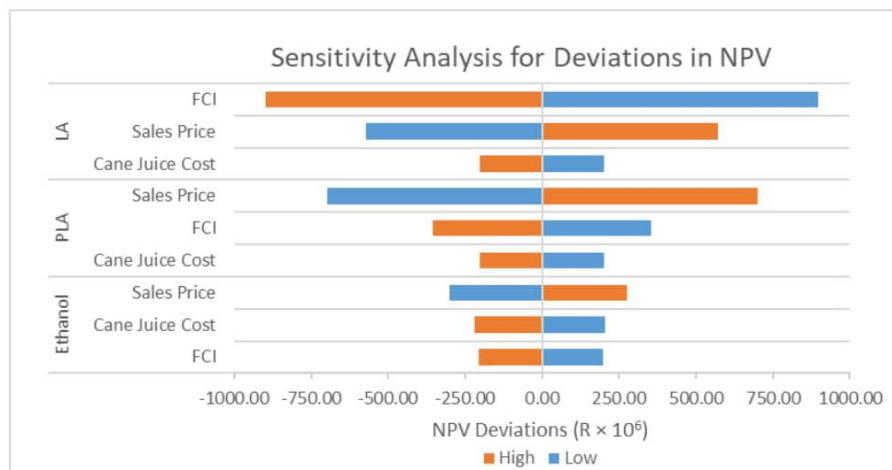


Figure 4. Tornado plot showing deviations to the baseline net present value when the fixed capital investment sales price and raw material costs are varied.

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.

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CHAPTER 4: PAPER II

Naidoo P *et al*

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REFEREED PAPER

S-BEAT: EXTENDING THE INVENTORY OF THE SUGARCANE BIOREFINERY ECONOMIC ANALYSIS TOOLBOX TO OTHER SUGAR MILL FEEDS AND PRODUCTS

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Introduction

The Sugarcane Biorefinery Economic Analysis Toolbox (S-BEAT) was developed to allow for quick, easy, and consistent comparisons between potential sugarcane-based products and processes, on a typical South African sugar mill scale. It was designed to provide preliminary cost estimates and economic insights, and can be utilised to help fast-track the industries' progression towards sustainability and economic growth.

Current challenges being faced by the South African sugar industry include and are not limited to the lack of transformation in the sector, high production costs, cheap sugar imports and lack of import regulations, as well as the understated implications of the tax on sugary beverages on the industry and the overall economy. The South African sugar industry is currently not capable of producing sugar at a cost that can compete on the global sugar market. However, 33.5% of its current production (672 277 t; 2017/18) is not consumed within the country (Madho *et al.*, 2018). Hence, the question arises whether this excess of sugar (or the equivalent in terms of sugar-containing mill streams) can be converted to biorefinery products (chemicals or materials) that may generate a higher revenue than the sales of sugar on the global market. This paper was constructed with these challenges in mind to help shed some light on the economic feasibility of potential bio-products.

Background

The preliminary cost estimation method that is utilised in S-BEAT was introduced at SASTA's 2018 Annual Congress (Naidoo *et al.*, 2019). A summary of the methodology is illustrated in Figure 1.

S-BEAT employs the order-of-magnitude (OOM) method, which accepts and escalates historical data of an existing plant or valid literature, to account for the passage of time and/or major plant geographical changes. Adjustments are also made for differing plant capacities. Although the estimated accuracy of this method is in the range of $\pm 30\%$ (Sinnot, 2005) to $\pm 50\%$ (Brown, 2006), the resultant cost is considered suitable as a preliminary estimate. Products which pass this assessment stage should undergo a rigorous techno-economic assessment prior to any major decision-making.

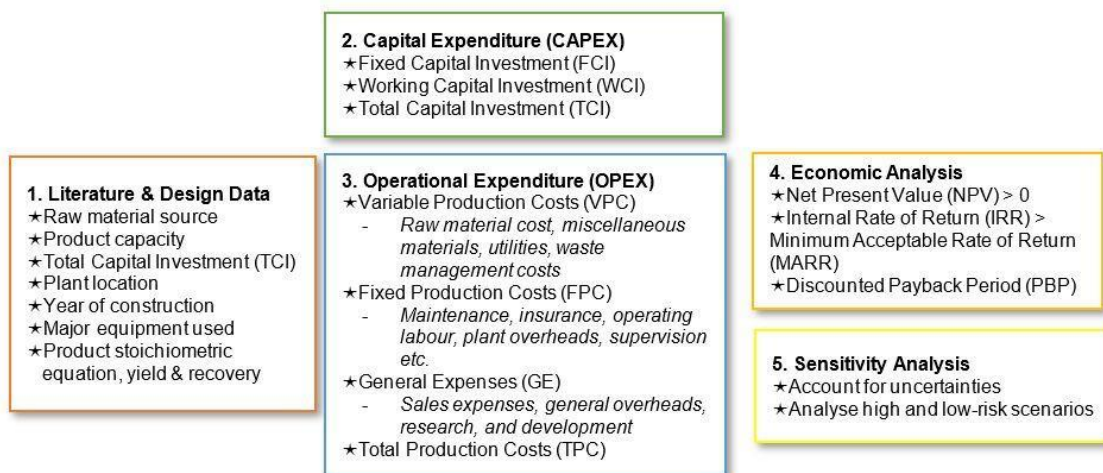


Figure 1. Summary of the input and output parameters and their abbreviations used in S-BEAT.

One of the shortcomings identified in the previous version of S-BEAT (Naidoo *et al.*, 2019) was that the method could only estimate the economic potential of products originating from the sugar mill's clear juice stream, with an estimated clear juice cost. Overcoming this limitation was ranked as a priority for the progression of S-BEAT. A methodology is currently being developed by the Sugar Milling Research Institute NPC (SMRI) to assess the value of the intermediate sugar mill streams. The generic Sugar Mill MATLAB[®] model with an upgraded utilities module was selected as the basis for the cost estimation of a greenfield sugar mill (Starzak and Davis, 2017; Foxon and Starzak, 2018). Furthermore, the economic assessment portfolio was extended to include further potential biorefinery products, in addition to high density polyethylene and polylactic acid. The portfolio now includes:

- From clear juice: ethanol (EtOH-CJ), ethylene (ethylene-CJ), succinic acid (SA-CJ), 1,4-butanediol (1,4-BDO-CJ), monoethylene glycol (MEG-CJ),
- From syrup: lactic acid (LA-Syrup), polylactic acid (PLA-Syrup), L-lysine hydrochloride (lysine-Syrup), 2,5-furandicarboxylic acid (FDCA-Syrup),
- From A-molasses: L-lysine hydrochloride (lysine-Mol), 2,5-furandicarboxylic acid (FDCA-Mol).

For the costing of the intermediate sugar-containing mill streams, the generic sugar mill was separated into modules, i.e. an extraction module to obtain mixed juice, a clarification module for clear juice, an evaporation module for syrup, and an A-station for A-sugar and A-molasses. The B and C stations were grouped together to obtain the C-molasses cost, and a drying module for the final raw sugar stream was used. The internal heating and cooling process streams were calculated as well to fulfil the overall mill cost balance. Calculations were performed to obtain the total capital investment required¹ and the direct production costs associated with each module in the mill.

The costs of the previously mentioned mill streams were obtained with a simple cost balance, i.e. the output stream cost of one module is equivalent to the input stream cost to this module, plus the direct production costs (i.e. the fixed production costs and the variable production costs less the raw material cost). The cost calculation is done to ensure that the economics of the sugar mill do not change, i.e. the mill is being compensated for the loss in sugar production by the value of the diverted stream. It bears mentioning that the results of the intermediate mill

¹ CAPEX and OPEX data were obtained through discussions with sugar industry representatives.

streams are only valid for the configuration and assumptions that were used in the generic sugar mill model; these results would therefore differ between mills.

This approach allows for the diversion of (parts of) the streams to potential downstream biorefinery operations. It needs to be noted that the sugar mill equipment capacity (250 tons cane per hour) was not adjusted to a lower sugar throughput for the scenarios whereby the mill stream was diverted from the sugar production, as it is assumed that it would remain installed as is, in order to be flexible to answer market changes. In other words, sugar is assumed to be produced in the mill with the same efficiency and cost.

Ethanol (EtOH), ethylene and monoethylene glycol (MEG)

The conventional petrochemical route to monoethylene glycol (MEG) involves the steam cracking of a light hydrocarbon to produce ethylene, which is then oxidised to ethylene oxide. The ethylene oxide is then reacted to ethylene carbonate, which undergoes hydrolysis to form ethylene glycol. The production pathway of ethylene is the only difference in the bio-based route to MEG: sugar undergoes fermentation to produce ethanol and the ethanol is dehydrated to form ethylene.

Bio-MEG can be directly substituted for petroleum-based MEG in the production of polyethylene terephthalate (PET), which is used to make packaging, bottles, films and textiles. Other uses for MEG include antifreeze, dehydrating and dewatering solvents, industrial solvents and coolants (Jogdand, 2015). The revenue from MEG is expected to reach \$37.07 billion by 2026, and the top producers of MEG are currently the Dow Chemical Company, Royal Dutch Shell PLC, Saudi Basic Industries Corporation (SABIC), BASF SE, and LyondellBasell Industries N. V. (Maximize Market Research PVT Ltd, 2018)².

Table 1 shows the literature information used to calculate the capital expenditure of ethanol, ethylene and monoethylene glycol plants. It should be noted that the CAPEX and OPEX are estimated separately for each process. However, the discussions of the economic results pertain to the overall plant, i.e. for the production of ethylene, the ethanol and the ethylene plant are considered, while for economic assessment of the production of MEG, the ethanol, ethylene and MEG plants are taken together. The major equipment that is required for the OPEX costing can be found in the literature source material.

Table 1. Literature data used to calculate the CAPEX of the ethanol, ethylene and MEG plants.

Product	Ethanol ^a	Ethylene ^b	MEG ^c
Literature source	A Virtual Sugarcane Biorefinery	Intratec Solutions – ‘Green Ethylene Production’	Intratec Solutions – ‘Ethylene Glycol Production’
Raw material source	Sugarcane	Ethanol	Ethylene
Product capacity	84 000 t/a	300 000 t/a	750 000 t/a
Total capital investment	\$32 840 830	\$260 000 000	\$630 000 000
Reference location	Brazil	US Gulf Coast	US Gulf Coast

² Maximize Market Research (2018). *Monoethylene Glycol (MEG) Market – Global Industry Analysis and Forecast (2017-2026)*. [Online] Available at: <https://www.transparencymarketresearch.com/monoethylene-glycol-market.html> [Accessed 15 January 2019].

Reference year	2014	2014	2015
Stoichiometric equation	$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$	$C_2H_5OH \rightarrow C_2H_4 + H_2O$	$C_2H_4 + 0.5O_2 \rightarrow C_2H_4O$ $C_2H_4O + CO_2 \rightarrow C_3H_4O_3$ $C_3H_4O_3 + H_2O \rightarrow C_2H_6O_2 + CO_2$
Product yield	$C_2H_5OH = 90\%$	$C_2H_4 = 99\%$	$C_2H_4O = 88\%$ $C_3H_4O_3 = 93.1\%$ $C_2H_6O_2 = 99.5\%$
Separation recoveries	997%	99.9%	99% (assumed)

^a (Bonomi et al., 2016), ^b (Jenkins, 2015a), ^c (Jenkins, 2015b)

2,5-Furandicarboxylic acid (FDCA)

FDCA is a renewable organic compound that can be used as a replacement chemical for several petroleum-based platform chemicals such as terephthalic acid, bisphenol A, isophthalic acid, phthalic anhydride and adipic acid. Other applications include insecticides, fire foams, pharmaceuticals, antibacterial agents and agrochemicals (Anon., 2012).

In the bio-based process, fructose is obtained by inversion of glucose. It then undergoes an acid catalysed reaction to form 5-hydroxymethylfurfural (5-HMF). For stability reasons, 5-HMF is reacted with methanol to yield the more stable 5-methoxymethylfurfural (MMF). The last step in the process involves the oxidation of MMF to FDCA.

The market potential for FDCA is expected to grow to \$498.2 million by 2020 with an expected volume of 498.15 kt. One of the market drivers includes the demand for carbonated soft drinks and hence bottles made from FDCA. The key players are currently AVA Biochem, Avantium, Corbion, Synbias and Tokyo Chemical Industry (Grand View Research, 2015a)³.

The information that is required to estimate the CAPEX of the 2,5-furandicarboxylic acid process is found in Table 2. The major equipment that is required for the OPEX costing can be found in the literature source material.

Table 2. Literature data used to calculate the CAPEX of the 2,5-furandicarboxylic acid plant.

Product	2,5-Furandicarboxylic acid ^d
Literature source	Intratec Solutions – 'Green FDCA Production'
Raw material source	70 wt. % glucose syrup inverted to fructose
Product capacity	300 000 t/a
Total capital investment	\$600 000 000
Reference location	US Gulf Coast
Reference year	2015
Stoichiometric equation	$C_6H_{12}O_6 \rightarrow C_6H_6O_3 + 3H_2O$ $C_6H_6O_3 + CH_3OH \rightarrow C_7H_8O_3 + H_2O$ $C_7H_8O_3 + 1.5 O_2 \rightarrow C_6H_4O_5 + CH_3OH$
Product yield	$C_6H_6O_3 = 77\%$ ^e , $C_7H_8O_3 = 78\%$ ^f , $C_6H_4O_5 = 98\%$ ^g
Separation recoveries	99% ^g

^d (Jenkins, 2015c), ^e (Chernyshev et al., 2017), ^f (Bicker et al., 2005), ^g (Almeida et al., 2018)

Lactic acid (LA) and polylactic acid (PLA)

³ Grand View Research (2015a). *Global FDCA Market Potential by Application expected to reach USD 498.2 million by 2020*. [Online] Available at: <https://www.grandviewresearch.com/press-release/global-fdca-market> [Accessed 12 February 2019].

The production process for polylactic acid begins with the fermentation of a sugar substrate to lactic acid. The lactic acid undergoes a dimerisation to lactide, followed by ring opening polymerisation of the lactide (Jenkins, 2015e).

Table 3. Literature data used to calculate the CAPEX of the lactic acid and polylactic acid plants.

Product	Lactic Acid ^h	Polylactic Acid ⁱ
Literature source	Intratec Solutions – “Lactic Acid Production via Glucose Fermentation “	Intratec Solutions – “Production of Polylactic Acid”
Raw material source	70 wt. % glucose syrup	Lactic acid
Product capacity	100 000 t/a	100 000 t/a
Total capital investment	\$200 000 000	\$100 000 000
Reference location	US Gulf Coast	US Gulf Coast
Reference year	2015	2015
Stoichiometric equation	$C_6H_{12}O_6 \rightarrow 2C_3H_6O_3$	$2C_3H_6O_3 \rightarrow C_6H_8O_4 + 2H_2O$ $nC_6H_8O_4 \rightarrow (C_3H_6O_2)_nH_2O + (n-1)H_2O$
Product yield	Lactic acid = 91.86 %	Lactide = 94%, PLA = 95%
Separation recoveries	88.00	99.7%

^h(Jenkins, 2015d), ⁱ(Jenkins, 2015e)

The lactic acid market has been dominant in the pharmaceutical, cosmetic and food industries. There has been a large increase in the demand for the polymerised form of lactic acid, polylactic acid (PLA), because of its biodegradability. PLA can replace petroleum-based plastics in the packaging sector, and it also has application in the agriculture, electronics, textiles and transport sectors. In 2017, the market size for PLA was at an estimated high of \$ 950.7 million with the key players being: Total Corbion, Nature Works LLC, Hitachi, Ltd., and BASF SE (Grand View Research, 2018)⁴.

The literature data utilised in the cost estimates for lactic acid and PLA can be found in Table 3. The major equipment that is required for the OPEX costing can be found in the literature source material.

L-Lysine hydrochloride

Lysine is an amino acid that is commercially produced as L-lysine hydrochloride. It cannot be produced naturally in humans or other monogastric animals, although it is vital to their bodies as it enhances proper growth. Hence, lysine plays a large role in animal nutrition and is commonly used as animal feed additive (Grand View Research, 2015c)⁵.

It is industrially produced by a microbial fermentation of a sugar-containing substrate and hence it is highly reliant on the price and availability of this raw material feed. The application of lysine as animal feed, food and dietary supplement and in pharmaceuticals is expected to reach \$6.96 billion by 2020 with an estimated quantity of 2 854.9 kt (Grand View Research, 2015b)⁶. Some of the major players include Ajinomoto Ltd, Archer Daniel Midland (ADM),

⁴ Grand View Research (2018). Polylactic Acid (PLA) Market Size, Share & Trends Analysis Report 2018 – 2025. [Online] Available at: <https://www.grandviewresearch.com/industry-analysis/polylactic-acid-pla-market> [Accessed 17 February 2019].

⁵ Grand View Research (2015c). *Lysine Market Analysis by Application and Segment Forecasts To 2020*. [Online] Available at: <https://www.grandviewresearch.com/industry-analysis/lysine-market> [Accessed 17 February 2019].

⁶ Grand View Research (2015b). *Global Lysine Market Expected to reach USD 6.96 Billion by 2020*. [Online] Available at: <https://www.grandviewresearch.com/press-release/global-lysine-market> [Accessed 17 February 2019].

Global Biochem Tech, Cheil Jedang Corp., and Evonik Industries (Grand View Research, 2015b).

The literature data required for the CAPEX calculations of lysine can be found in Table 4. The major equipment that is required for the OPEX costing can be found in the literature source material.

Table 4: Literature data used to calculate the CAPEX of the L-lysine hydrochloride plant.

Product	L-Lysine hydrochloride ^j
Literature source	Intratec Solutions – “L-Lysine Hydrochloride Production from Glucose”
Raw material source	70 wt.% glucose syrup
Product capacity	100 000 t/a
Total capital investment	\$350 000 000
Reference location	US Gulf Coast
Reference year	2016
Stoichiometric equation	$7C_6H_{12}O_6 + 12NH_3 \rightarrow 6C_6H_{14}N_2O_2 + 6CO_2 + 18H_2O$ $C_6H_{14}N_2O_2 + HCl \rightarrow C_6H_{15}ClN_2O_2$
Product yield	78.8 %
Separation recoveries	98.5 %

^j(Jenkins, 2016)

Succinic acid (SA) and 1,4-butanediol (1,4-BDO)

In the petroleum-based route to succinic acid, butane is oxidised to form maleic anhydride (MAN) which undergoes hydrolysis to form succinic acid. The biomass-based route proceeds via the fermentation of a sucrose substrate to succinic acid. Bio-based succinic acid can be directly substituted for its petroleum counterpart since their structures are identical. Succinic acid can be used to produce 1,4-butanediol (1,4-BDO), tetrahydrofuran (THF), gamma-butyrolactone (GBL) etc. When succinic acid and 1,4-BDO are reacted, they form the biodegradable polymer polybutylene succinate (PBS), which is used in the production of bioplastics (Jogdand, 2015). 1,4-Butanediol can also be reacted with terephthalic acid to form polybutylene terephthalate (PBT), a plastic which is used for a wide range of applications in the automotive industry (E4tech, RE-CORD, WUR, 2015).

By 2025, the global market for 1,4-BDO is expected to grow to \$12.5 billion and the key players are currently BioAmber Inc., ExxonMobil Chemicals, LyondellBasell Industries, the Dow Chemical Company, BASF SE, Genomatica and Myriant Corporation (AnalystView Market Insights, 2018)⁷.

The literature data used to calculate the CAPEX of succinic acid and 1,4-butanediol are found in Table 5. The major equipment that is required for the OPEX costing can be found in the literature source material.

Table 5. Literature data used to calculate the CAPEX of the succinic acid and 1,4-butanediol plants.

Product	Succinic Acid ^k	1,4-Butanediol ⁿ
Literature source	“Production of Bio-based Succinic Acid” by Intratec solutions	“1,4-Butanediol from Bio-Succinic Acid” by Intratec Solutions

⁷ AnalystView Market Insights (2018). *1,4 Butanediol (BDO) Market Size Worth \$12.5 Billion By 2025 | CAGR: 6.5%*. [Online] Available at <https://www.analystviewmarketinsights.com/press-release-14-butanediol-bdo-market> [Accessed 12 February 2019].

Raw material source	Cane Juice - assumed clear juice	Bio- succinic acid in water
Product capacity	77 000 t/a	55 000 t/a
Total capital investment	\$260 000 000	\$100 000 000
Reference location	US Gulf Coast	US Gulf Coast
Reference year	2014	2013
Stoichiometric equation	$7C_6H_{12}O_6 + 6CO_2 \rightarrow 12C_4H_6O_4 + 6H_2O$	$C_4H_6O_4 + 4H_2 \rightarrow C_4H_{10}O_2 + 2H_2O$
Product yield	94% ^l (assumed)	90%
Separation recoveries	95% ^m	99.5%

^k (Jenkins, 2014a), ^l (Chan *et al.*, 2011), ^m (Nghiem *et al.*, 2017), ⁿ (Jenkins, 2014b)

CAPEX and OPEX: Results and Discussion

Case study basis

The design basis for this study is that the biorefinery additions would be integrated with a 250 tch South African sugar mill. The design year ended on 31st Dec. 2018. The feed flowrate was specified as either 50% of a clear juice stream, 50% of a syrup stream, or 60% of an A-molasses stream (diverted from either one or two mills). The properties of the streams, which were obtained from the mill model during the development of the costing methodology for intermediate mill streams, are shown in Table 6, where the molasses flowrate is of the 60% that is diverted to the biorefinery.

For all fermentations, i.e. ethanol, lactic acid, lysine, and succinic acid, it is assumed that the microorganism/enzyme used is not substrate specific and will hence convert sucrose to glucose and fructose, and both monosaccharides to the respective product. Furthermore, since the composition of the non-sugar fraction with regards to fermentable sugars is not exactly known, the contained glucose and fructose were not taken into consideration in yield calculations, i.e. yields may be underestimated. The literature data for L-lysine hydrochloride, lactic acid and FDCA are based on a 70 mass % glucose feed. The mill model indicates a Brix of 64.8% for the syrup stream and 74.5% Brix for the A-molasses stream. It was assumed that these streams would generate similar outcomes (yields and recoveries) as the literature glucose feed. Additionally, it was assumed that the steam, electricity, and water utilities generated by the sugar mill would be sufficient to run the downstream biorefinery additions.

Table 6. Selected stream properties of clear juice, syrup and A-molasses, as well as their stream costs.

Stream property	Clear juice	Syrup	A-molasses ^o
Flow (t/h)	296.02	59.69	8.73
Water (%)	86.67	35.18	25.54
Sucrose (%)	11.49	55.73	53.93
Non-sucrose (%)	1.84	9.10	20.53
Brix (%)	13.33	64.82	74.46
Stream cost (R/t)	368	1 980	2 030

^o The A-molasses stream flow rate and stream cost corresponds to the case whereby 60% of the A-molasses stream is diverted to a biorefinery

The default operational days, hours and shifts were selected as 252 days, 24 hours and 3 shifts, respectively. An average exchange rate over the year 2018 of ZAR13.29/USD was applied where necessary. A location factor of 60.8 (Schwab, 2018) was used for South Africa and a Chemical Engineering Plant Cost Index (CEPCI) of 612.7 for the year 2018 was used (Anon., 2018). The cost of the intermediate sugar mill streams, as determined in current work

conducted at the SMRI, for the generic mill model, were clear juice at R368/t, syrup at R1 980/t and A-molasses (60% diversion to biorefinery) at R2 030/t. The cost of cane was calculated to be R499/t and the cost of bagasse was calculated as its coal equivalent cost to be R431/t.

It should be noted that S-BEAT was previously introduced on the examples of ethanol/ethylene/HDPE and lactic acid/PLA, produced using 50% of a clear juice stream. However, at that stage of the toolbox development, clear juice costs were estimated, and the design year was 2016 (Naidoo *et al.*, 2019). Since for this paper, the majority of literature plant references were obtained from Intratec Solutions, the input parameters for lactic acid were changed accordingly to allow for a higher confidence in the degree of comparability. The location factor used in the previous study (Naidoo *et al.*, 2019) was the Deloitte manufacturing competitiveness index. For this present study, the World Economic Forum (WEF) global competitiveness index was used to account for the change in geographical locations for the 2018 biorefinery (Schwab, 2018). The project lifetime was originally taken to be 20 years; however, this has been changed to 25 years in the present study. A rigorous assessment of the effects of stream diversion on the economics of the mill has not been carried out, as the mill is compensated by the sale of the intermediate stream to ensure that its economics are still feasible. An assessment of the different revenues generated in comparison to the raw sugar revenue is discussed.

Results and Discussion

The following product analysis is presented according to the three different feedstock cases, i.e. clear juice, syrup, and A-molasses. Firstly, the CAPEX and OPEX were analysed for lactic acid and its polymer PLA, as well as FDCA and lysine from the syrup stream (Table 7). The Fixed Capital Investment (FCI) results show that lysine requires the largest capital investment followed by PLA, FDCA and lactic acid. It must be noted that the FCI and Total Production Costs (TPC) for polylactic acid is the summation of the values for the lactic acid and PLA facilities and is represented by PLA^F-Syrup (where *F* represents the final product). The TPC required followed the same trend.

Table 7: CAPEX and OPEX results for lactic acid, polylactic acid, FDCA and lysine from the syrup stream.

Parameters		LA-Syrup	PLA-Syrup	PLA ^F -Syrup	FDCA-Syrup	Lysine-Syrup
CAPEX	Feed stream	Syrup	LA-Syrup	Syrup	Syrup	Syrup
	Feed capacity (t/a)	180 503	81 319	180 503	180 503	180 503
	Product capacity (t/a)	81 319	57 920	57 920	50 279	67 851
	Capacity exponent	0.67	0.67	0.67	0.67	0.67
	CEPCI	556.8	556.8	556.8	556.8	541.7
	Location factor	85.6	85.6	85.6	85.6	85.6
	FCI (R × 10 ⁶)	1 709.70	681.01	2 390.71	1 780.21	2 724.03
OPEX	Raw material cost (R × 10 ⁶ /a)	357.48	-	357.48	357.48	357.48
	Operating labour (R × 10 ³ /a)	1 316.34	1 447.97	2 764.31	1 711.24	1 184.71
	VPC (R × 10 ⁶ /a)	441.96	11.27	453.23	443.17	457.57
	FPC (R × 10 ⁶ /a)	107.06	45.58	152.64	112.03	167.67
	TPC (R × 10 ⁶ /a)	584.06	60.48	644.54	590.63	665.15

To investigate the use of S-BEAT for the comparison of a product derived from two different feed sources, the economics of lysine or FDCA production were also assessed from A-molasses as the feedstock (Table 8). Two scenarios were considered: either 60% of the A-molasses was diverted from one mill, or 60% of the molasses of two mills were processed together, leading to an increased plant capacity of factor two. The reason for not diverting 100% from one mill instead was that it was thought that the B and C-stations would have to remain operational. Table 8 tabulates the results of this comparison. Hence, due to the non-linear relationship between capacity and FCI (economies of scale), a doubled capacity leads to a less than two-fold FCI. The impact of this on the economic feasibility will be discussed in a subsequent section.

Table 8: CAPEX and OPEX results for lysine and FDCA from the A-molasses stream.

Parameters		Lysine-Mol	FDCA-Mol	Lysine-Mol	FDCA-Mol
CAPEX	Feed stream	60% A-molasses from 1 mill	60% A-molasses from 1 mill	60% A-molasses from 2 mills	60% A-molasses from 2 mills
	Feed capacity (t/a)	52 788	52 788	105 576	105 576
	Product capacity (t/a)	19 202	14 229	38 404	28 458
	Capacity exponent	0.67	0.67	0.67	0.67
	CEPCI	541.7	556.8	541.7	556.8
	Location factor	85.6	85.6	85.6	85.6
	FCI ($R \times 10^6$)	1 169.27	764.14	1 860.39	1 215.80
OPEX	Raw material cost ($R \times 10^6/a$)	107.13	107.13	214.27	214.27
	Operating labour ($R \times 10^3/a$)	1 184.70	1 711.24	1 184.70	1 711.24
	VPC ($R \times 10^6/a$)	143.05	136.96	278.05	268.29
	FPC ($R \times 10^6/a$)	74.38	51.06	115.85	78.16
	TPC ($R \times 10^6/a$)	231.31	200.02	419.04	368.53

Ethanol, ethylene and MEG were produced from clear juice streams (Table 9). The overall cost of the ethylene facility is the cost of ethanol and the cost of the ethylene production, and the overall cost of MEG is the cost of the ethanol, ethylene and MEG facilities. The column labeled MEG^F-CJ is representative of this, where *F* is the final product in the process.

Table 9: CAPEX and OPEX results for ethanol, ethylene, MEG from a clear juice mill stream.

Parameters		EtOH-CJ	Ethylene-CJ	MEG-CJ	MEG ^F -CJ
CAPEX	Feed stream	Clear Juice	EtOH-CJ	Ethylene-CJ	Clear Juice
	Feed capacity (t/a)	895 165	47 200	28 422	895 165
	Product capacity (t/a)	47 200	28 422	50 756	50 756
	Capacity exponent	0.90	0.83	0.67	0.67
	CEPCI	576.1	576.1	556.8	-
	Location factor	59.5	85.6	85.6	-
	FCI ($R \times 10^6$)	266.89	348.95	1 018.09	1 633.93
OPEX	Raw material cost ($R \times 10^6/a$)	329.18	-	-	329.18
	Operating labour ($R \times 10^3/a$)	789.80	1 184.71	1 579.61	3 554.12
	VPC ($R \times 10^6/a$)	386.68	6.06	16.51	409.25
	FPC ($R \times 10^6/a$)	19.50	25.16	66.05	110.71
	TPC ($R \times 10^6/a$)	432.11	33.22	87.83	553.16

The CAPEX and OPEX values differ from the previous study (Naidoo *et al.*, 2019) due to the different clear juice capacity which now accounts for both monosaccharides and not just the glucose. This was done for all the products under the assumption that the fermentation microorganisms are not substrate specific. Additionally, the adjustment in the feedstock cost played a big role in the OPEX calculations.

Table 10 shows the results of the CAPEX and OPEX of succinic acid and 1,4-BDO from clear juice. As with the PLA production, the FCI and TPC of 1,4-BDO are summations of the succinic acid and 1,4-BDO facilities. This is represented by the column labelled 1,4- BDO^F-CJ, where *F* stands for final product. The FCI and TPC are quite high for the succinic acid; however, they correspond to a product capacity of 103 210 t/a.

Table 10. CAPEX and OPEX results for SA and 1,4-BDO from a clear juice mill stream.

Parameters		SA-CJ	1,4-BDO-CJ	1,4-BDO ^F - CJ
CAPEX	Feed stream	Clear Juice	SA-CJ	Clear Juice
	Feed capacity (t/a)	895 165	103 210	895 165
	Product capacity (t/a)	103 210	70 535	70 535
	Capacity exponent	0.67	0.67	0.67
	CEPCI	576.1	567.3	-
	Location factor	85.6	85.6	85.6
	FCI (R × 10 ⁶)	3 002.48	1 138.50	4 140.98
OPEX	Raw material cost (R × 10 ⁶ /a)	329.18	-	329.18
	Operating labour (R × 10 ³ /a)	1 711.24	1 316.34	3 027.58
	VPC (R × 10 ⁶ /a)	429.18	18.29	447.47
	FPC (R × 10 ⁶ /a)	185.36	72.78	258.14
	TPC (R × 10 ⁶ /a)	653.77	96.88	750.65

Economic and Sensitivity Analysis: Results and Discussion

Economic Parameters

A Discounted Cash Flow (DCF) analysis is used to determine the Net Present Value (NPV), Internal Rate of Return (IRR) and discounted Pay-Back Period (PBP) for the different products. The economic parameters utilised in the DCF are as follows: the plant lifetime was pre-defined as 25 years for each potential process. Arbitrary percentages of 3.5% and 1.0% increases 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 Minimum Acceptable Rate of Return (MARR) was taken as 20% for this study. The NPV is hence calculated, at the end of 25 years, with a MARR of 20% and the discounted PBP is the year in which the cumulative discounted cash flows become positive. The IRR, on the other hand, is obtained by varying the MARR until the NPV of the plant becomes zero.

Price Analysis

The market price that was used for the comparison of each product of interest is listed below. These prices were acquired from previous studies and market data, and were escalated to 2018, where necessary, and converted to R/t. The final prices that were used as inputs to the DCF are presented in Table 11 along with the cost of production per ton of product that is required for the generic mill model with the appended biorefinery. The cost of production can be regarded as the minimum price that the product can be sold for, without making profit.

- A succinic acid production cost in 2017 of \$1.17/kg (Nghiem *et al.*, 2017) was used.
- For 1,4-BDO, a value of \$2 287/t was obtained from a 2013 market price report on 1,4-BDO (Anon., 2013).
- In 2016, the Chinese lysine market experienced major fluctuations in its price from \$1.2/kg – \$1.8/kg (Anon., 2017)⁸. A best-case scenario of \$1.8/kg was assumed for this study.
- Although a 2012 report on FDCA suggested that the price of FDCA should go down to \$1 000/t in 2016 (Anon., 2012), a value of \$1 400/t was assumed.
- The price of lactic acid was obtained for May 2017 at a value of \$1 240/t (Qingdao Echemi Technology Co. Ltd, 2019)⁹.
- A US based export price of \$1 910/t from October 2017 was used for the PLA assessment (Plastics Insights, 2019b)¹⁰. The US price is lower than other countries (China - \$4 770/t; Germany - \$2 642/t) and is hence the worst-case scenario in terms of product price.
- In 2014, the price of ethanol fluctuated between \$917/t and \$1 024/t in China, \$521/t and \$930/t in the US and between \$660/t and \$873/t in Brazil (Intratec Solutions LLC, 2017a)¹¹. An optimistic price of \$934/t of anhydrous ethanol was assumed in this study.
- The price of ethylene was obtained for February 2014 at \$1 173/t (Intratec Solutions LLC, 2017b)¹².
- The price of MEG at \$1 610/t in the US for the period of October 2017 was used (Plastics Insight, 2019a)¹³.

Table 11: The cost of production market prices used per product, where the market prices have been escalated to 2018 and converted to ZAR.

Product	Cost of production (R/t)	Market price used in the study (R/t)
SA-CJ	6 334	16 426
1,4-BDO-CJ	10 642	33 325
Lysine-Syrup	9 803	26 000
Lysine-Mol – 1 mill	12 046	26 000
Lysine-Mol – 2 mills	10 911	26 000
FDCA-Syrup	11 747	20 148
FDCA-Mol – 1 mill	14 057	20 148
FDCA-Mol – 2 mills	12 949	20 148
LA-Syrup	7 182	17 220
PLA-Syrup	11 128	26 447
EtOH-CJ	9 155	13 375
Ethylene-CJ	16 372	16 622
MEG-CJ	10 898	22 293

It can be seen that in all cases, the market prices used in the assessment are higher than the costs of producing the products. In terms of the product values, the lowest production costs

⁸ Anon. (2017). *High fluctuations in China's lysine market 2016 with a drop in 2017* [Online] Available at: <http://www.cnchemicals.com/Press/89210-Huge%20fluctuations%20in%20China%E2%80%99s%20lysine%20market%202016%20with%20a%20drop%20in%202017.html> [Accessed 26 March 2019]

⁹ Qingdao Echemi Technology Co. Ltd (2019). *Lactic Acid Price Market Analysis*. [Online] Available at: <http://www.echemi.com/productsInformation/pd20150901239-lactic-acid.html> [Accessed 25 January 2019]

¹⁰ Plastics Insight (2019b). *Polylactic Acid Properties, Production, Price, Market and Uses*. [Online] Available at: <https://www.plasticsinsight.com/resin-intelligence/resin-prices/polylactic-acid/#forecast> [Accessed 20 Feb 2019].

¹¹ Intratec Solutions LLC (2017a). *Ethanol Price History and Forecast* [Online] Available at <https://www.intratec.us/chemical-markets/ethanol-prices> [Accessed 26 March 2019]

¹² Intratec Solutions LLC (2017b). *Ethylene Price History and Forecast*. [Online] Available at: <https://www.intratec.us/chemical-markets/ethylene-price> [Accessed 22 February 2019].

¹³ Plastics Insight (2019a). *Mono-Ethylene Glycol (MEG): Production, Market, Price and its Properties* [Online] Available at: <https://www.plasticsinsight.com/resin-intelligence/resin-prices/mono-ethylene-glycol-meg> [Accessed 20 February 2019].

per ton of products were for succinic acid whilst the highest production cost was for production of FDCA from 60% of A-molasses diverted from one mill.

Economic Results

The revenue that is generated by each biorefinery product is presented in Table 12. Additionally, the revenue that would be generated by the sugar that is produced from the sugar mill is shown for the cases of no diversion, i.e. sugar production only, 50% diversion of clear juice, 50% of syrup diversion and 60% diversion of A-molasses from either one or two mills. A 2017 world market price of R 4 465/t sugar (Singels *et al.*, 2018) was applied, i.e. based on the assumption that all of the sugar would be sold as export sugar. The flow rate of sugar for each case was obtained from the preliminary costing methodology for the 250 t/h cane mill. For the case of no diversion, the flow rate of sugar would be 29.38 t/h (178 000 t/a) and it would generate R793 400 000 /a. The flow rate is halved for the diversion of clear juice and syrup, 14.69 t/h (89 000 t/a) and the revenue obtained is R396 700 000 /a. For the diversion of 60% of A-molasses the sugar flow rate is reduced to 23.13 t/h (140 000 t/a) which generates R624 700 000 /a. The revenue that is generated for each biorefinery product does not include the revenue from the sugar or any other co-product.

Table 12. Revenue generated by each biorefinery product.

Stream diverted	Product	Revenue (R/a)
No diversion	Raw sugar	793 400 000
Clear juice diversion	Raw sugar	396 700 000
	SA-CJ	1 695 000 000
	1,4-BDO-CJ	2 344 000 000
	EtOH-CJ	631 300 000
	Ethylene-CJ	472 400 000
	MEG-CJ	1 131 500 000
Syrup diversion	Raw sugar	396 700 000
	Lysine-Syrup	1 764 000 000
	FDCA-Syrup	1 013 000 000
	LA-Syrup	1 400 000 000
	PLA-Syrup	1 532 000 000
A-molasses diversion	Raw sugar	624 700 000
	Lysine-Mol – 1 mill	499 300 000
	Lysine-Mol – 2 mills	998 500 000
	FDCA-Mol – 1 mill	286 700 000
	FDCA-Mol – 2 mills	573 400 000

The NPV, IRR and the discounted PBP were calculated for each product. For the products from clear juice (Table 13), it is interesting to note that although the production of ethylene from clear juice has a negative NPV, and would hence not seem viable, its conversion to monoethylene glycol renders the overall process viable. The NPV of 1,4-BDO and succinic acid are higher than those of ethanol or MEG and decreases in the order 1,4-BDO > succinic acid > MEG > ethanol > ethylene. With regards to the IRR, the products can be ranked: ethanol > 1,4-BDO > MEG > succinic acid > ethylene. This trend is also reflected in the discounted pay-back period. Overall, although the PBP is longer for both the succinic acid and 1,4-BDO processes, the results obtained at the end of 25 years appear more favourable.

Table 13: Economic indicators for products which originate from the clear juice stream (the NPV and discounted PBP are calculated with a MARR of 20%, and the IRR is obtained when the NPV is zero).

Economic Results	MARR = 20%		NPV=0
	NPV (R×10 ⁶)	Discounted PBP (Years)	IRR (%)
EtOH-CJ	846.81	3	48.61
Ethylene-CJ	-415.95	>25	12.41
MEG-CJ	863.69	9	26.13
SA-CJ	1 226.98	10	24.90
1,4-BDO-CJ	2 252.74	8	26.49

The products which originate from the syrup mill stream are all feasible, and they can be ranked according to the NPV as lysine > lactic acid > PLA > FDCA. In terms of the IRR (and discounted PBP) the products can be ranked as lactic acid > lysine > PLA > FDCA (Table 14).

Table 14. Economic indicators for products originating from the syrup mill stream (the NPV and discounted PBP are calculated with a MARR of 20%, and the IRR is obtained when the NPV is zero).

Economic Results	MARR = 20%		NPV=0
	NPV (R×10 ⁶)	Discounted PBP (years)	IRR (%)
LA-Syrup	1 819.17	6	31.93
PLA-Syrup	1 318.58	8	26.47
Lysine-Syrup	1 830.79	7	27.86
FDCA-Syrup	41.12	22	20.28

Table 15 tabulates the results of lysine and FDCA from a molasses stream that is diverted from either one or two mills. The results show that the production of lysine from the diversion of A-molasses from two mills is the only feasible case. The results also show that the NPV is less negative and the IRR is higher for the products which were obtained from the molasses that is diverted from two mills rather than one mill. This highlights the importance of economies of scale: although molasses has a high potential to generate revenue (as it is a low value stream), a low volume would render the scale of operation uneconomical, especially in the case of FDCA.

Table 15: Economic indicators for products originating from the A-molasses mill stream (the NPV and discounted PBP are calculated with a MARR of 20%, and the IRR is obtained when the NPV is zero).

Economic results	MARR = 20%		NPV=0
	NPV (R×10 ⁶)	Discounted PBP (years)	IRR (%)
Lysine-Mol – 1 mill	-32.89	>25	18.56
Lysine-Mol – 2 mills	487.08	12	23.17
FDCA-Mol – 1 mill	-446.28	>25	12.34
FDCA-Mol – 2 mills	-360.15	>25	16.27

Sensitivity Analysis

A sensitivity analysis is required to assess the impact of the uncertainties that are present in the methodology. These uncertainties can range from the choice of an inaccurate location factor to the inherent imprecision of the order-of-magnitude method. In order to analyse the

magnitude of the uncertainty, the user of S-BEAT can choose between a single parameter, or a number of parameters.

For the purpose of demonstration, the sensitivity analysis for this set of processes and products was performed by varying simultaneously the FCI, feedstock cost and product market price (SP) (Table 11) and assessing the impact that these parameters have on the economic indicators NPV, IRR and discounted PBP. Three scenarios are considered:

1. Base scenario: 0% deviation on the FCI, feedstock cost and SP.
2. High-risk scenario: +10% deviation on FCI, +20% on feedstock cost and -10% deviation on the SP.
3. Low-risk scenario: -10% deviation on the FCI, -20% on feedstock cost and +10% deviation on the SP.

It bears mentioning that product comparisons can only be conducted between products which originate from the same raw material stream. However, the economics of a single product can be compared between different feedstocks. In this manner, the ability of S-BEAT to compare between products and product processes is illustrated.

Figure 2 shows the sensitivity analysis results for the NPV and IRR of each product that originates from the sugar mill syrup stream. The sensitivity analysis shows that the NPV of FDCA is negative during high-risk scenarios, whilst the NPVs of lysine, lactic acid and PLA are consistently positive (albeit low for the high-risk scenario of PLA).

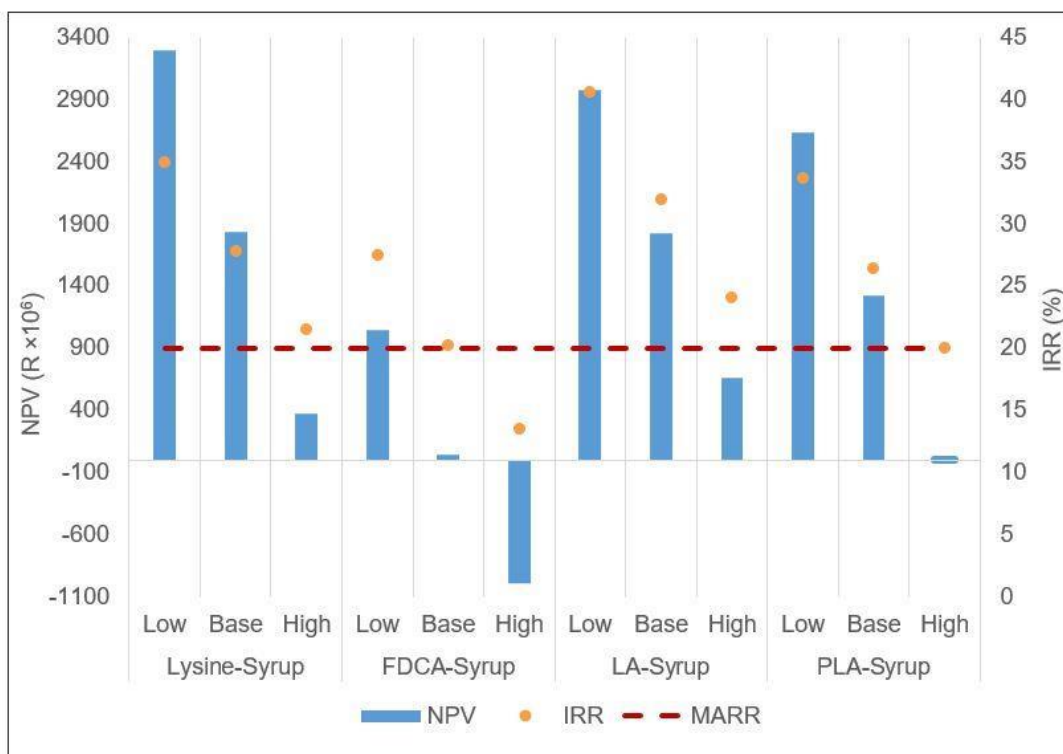


Figure 2. Sensitivity analysis for the products originating from the syrup feed stream.

Figure 3 depicts the results of the sensitivity analysis obtained for the products made from a clear juice stream. Ethanol and 1,4-BDO are the only products which do not have a negative NPV during the high-risk scenario case. The other products have negative NPVs when the selling prices are reduced and the FCI and raw material costs are increased. On the other hand, ethylene becomes feasible under a low-risk scenario.

Figure 4 shows the results of the sensitivity analysis when the syrup or A-molasses streams are used for either the production of lysine or FDCA. Only the scenario whereby 60% of the molasses stream is diverted from two mills is considered as it resulted in better economics than that of molasses diversion from one mill. The baseline and low-risk cases for both lysine and FDCA from syrup and lysine from A-molasses have positive NPVs, whilst the baseline and high-risk cases for FDCA from A-molasses have a negative NPV. However, for the low-risk cases, the production of FDCA from A-molasses does become viable. These results demonstrate that although molasses is a low-value by-product of the sugar industry, which could in principle contribute to value addition as a feedstock to an appended biorefinery operation, this is not easily achieved for all products, due to the low volumes available.

In order to determine which parameters played the greatest role in the variations that occur regarding the NPV, selected products (Lysine-A-Mol, MEG-CJ and SA-CJ) for which the NPVs were negative in the high-risk scenarios were further investigated using a tornado plot (Figure 5). The tornado plot varies one parameter at a time and looks at the effects that said variable has on the NPV of that product. The parameter which causes the greatest deviation in the NPV is represented by a longer bar in the tornado plot. The blue (minimum) bars are representative of a reduction in the parameter whilst the orange (maximum) bars are representative of an increase in the parameter.

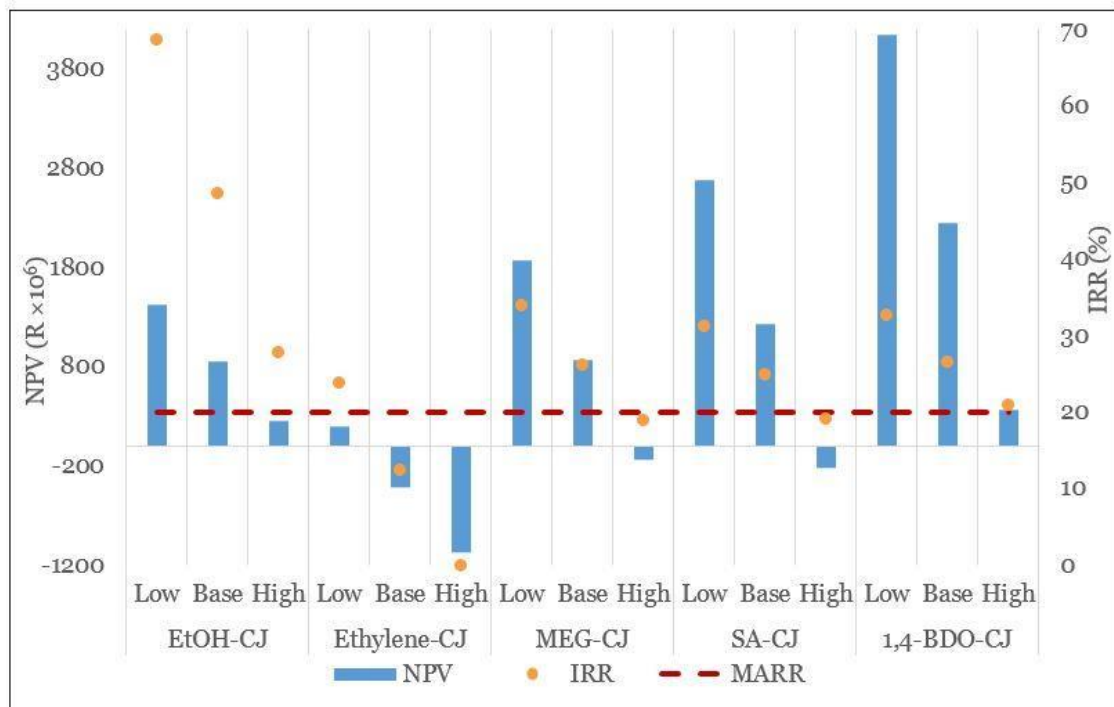


Figure 3. Sensitivity analysis for the products originating from the clear juice stream.

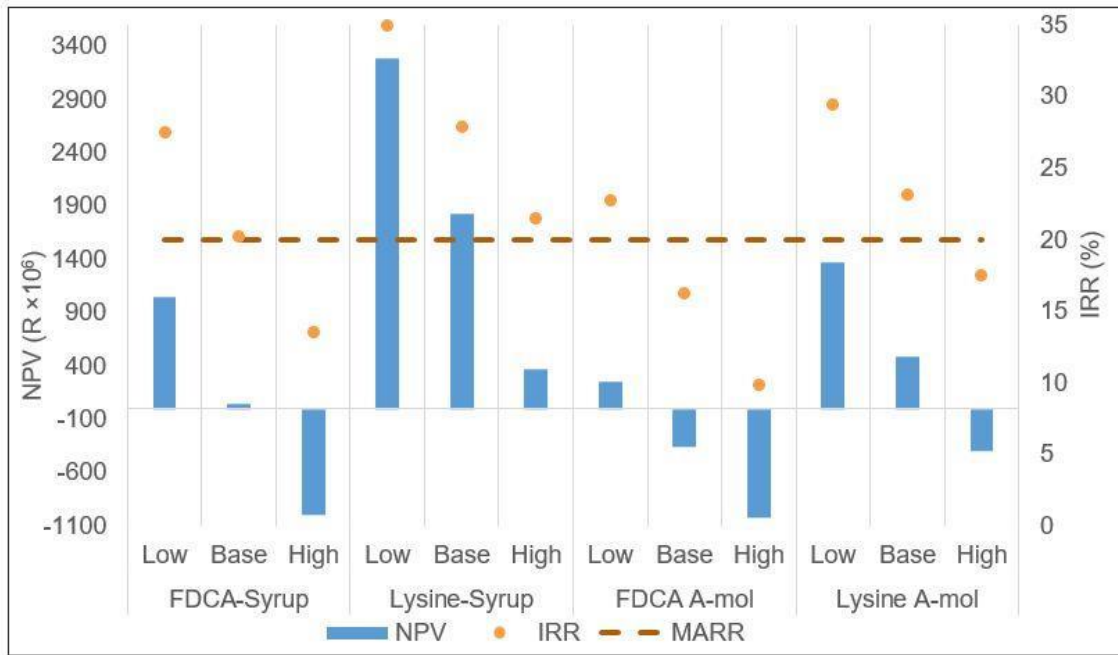


Figure 4. Sensitivity analysis comparing the lysine and FDCA production from either syrup or A-molasses (from two mills).

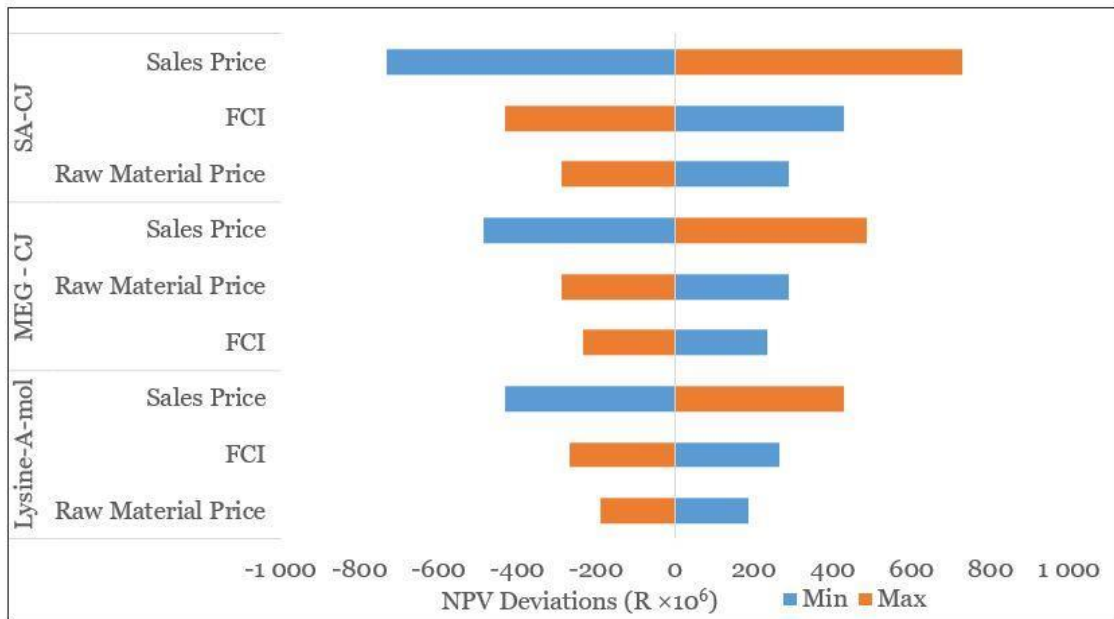


Figure 5. A tornado diagram showing which parameters have the greatest effects on the Lysine-A-mol from two mills, MEG-CJ and SA-CJ product NPVs.

Figure 5 indicates that for SA-CJ, MEG-CJ and Lysine-A-Mol, the reduction in the selling price is most responsible for the product becoming economically unviable. For SA-CJ and Lysine-A-mol, the second most impactful parameter is the FCI, which is an internal factor, and this suggests that process optimisation could improve the economics to render a positive NPV. For MEG-CJ, the raw material cost was the second most impactful parameter to affect the NPV. Since this cost is calculated based on default values within S-BEAT, company internal values should be used to test the effect on the overall economics.

Overall product feasibility

Figure 6 displays a summary of the economics of the products identified as being feasible in this study. The size of the bubbles is an indication of the IRR. The green circles depict the products which do not become unfeasible in the high-risk case, while the processes represented by orange circles become unfeasible during the high-risk scenarios. Although comparisons should only be made between products which originate from the same feedstock, for decision making, such a representation of the data provides a quick overview: Products with a short pay-back period and high NPV are more attractive, especially when the high- and low-risk cases result in a positive NPV (green circles).

Of the products and processes considered here, ethanol and 1,4-BDO produced from clear juice, and lysine, lactic acid and PLA produced from syrup, were the most feasible. MEG is also an economically viable product in terms of the shorter pay-back period, although it becomes negative in the high-risk scenario. Figure 5 shows which parameters need to be investigated more closely so that the MEG can be produced from clear juice profitably. FDCA from syrup was of a lower priority as it had a very low NPV with a very high pay-back period.

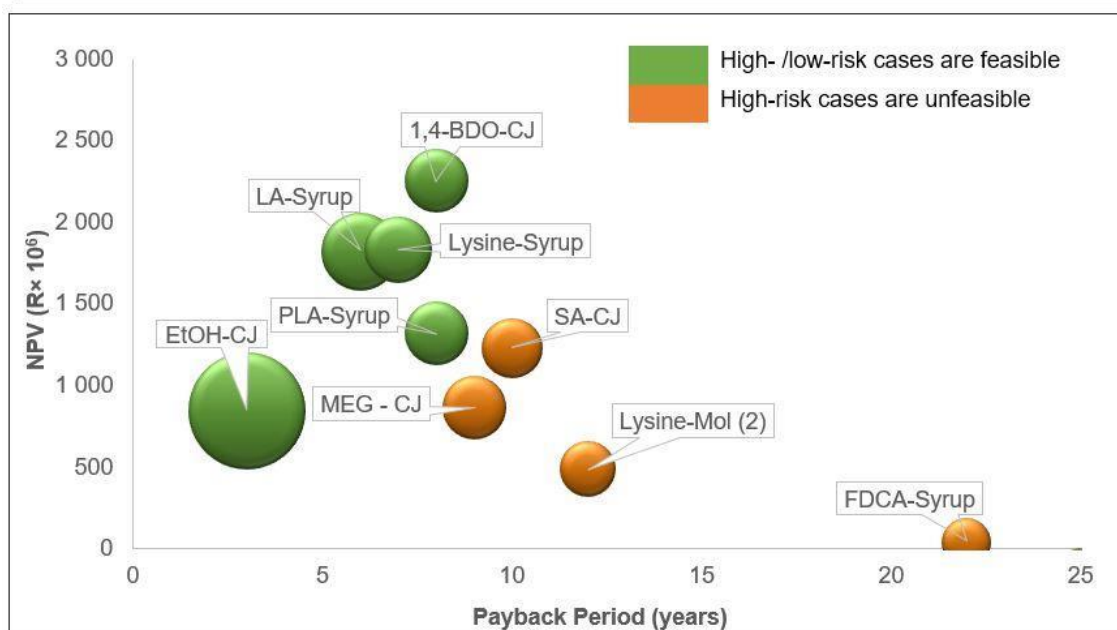


Figure 6. Summary of the feasibility of the potential products investigated in this study.

Conclusions

In conclusion, S-BEAT has shown that it can compare the economics of different products which start from the same intermediate mill stream, as well as of the same product from different streams. S-BEAT uses the NPV, IRR and discounted pay-back to allow for informed decisions to be made on product feasibility. From the case studies considered, ethanol and 1,4-BDO from clear juice and lysine, lactic acid and PLA from a syrup stream look like promising candidates. In addition, S-BEAT can be used to perform a sensitivity analysis on products by defining high- and low-risk scenarios. It hence provides support for decision making regarding the choice of biorefinery processes to be annexed to South African sugar mills.

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4.1 Discussion of paper 1 and paper 2 results

Different conditions were employed between papers 1 and 2, and therefore direct comparisons should not be made. For example, the basis of paper 1 was 2016, the time adjustment and the location adjustments would have been different from that of the 2018-based paper 2. Nevertheless, there are some glaring differences which were investigated. For example, investigation of ethanol in papers 1 (ethanol-1) and 2 (ethanol-2) had different outcomes. Ethanol-1 had an NPV of R 51.14 million whilst the NPV of ethanol-2 was R 846.81 million. This raises a question on the origin of the extreme difference and whether one or multiple factors were responsible for the difference. The clear juice was used to produce ethanol in both papers. However, the raw material costs were different; ethanol-1 used a raw material cost of R 427.90 million whilst ethanol-2 used a raw material cost of R 329.18 million.

Additionally, some of the factors that were used in the OPEX table were adjusted in paper 2 (these adjustments can be found in Appendix B), the combination of the reduced selling price and OPEX factors led to a difference in the Total Production Cost, between ethanol-1 and ethanol-2, of R 224.65 million. The difference in the Fixed Capital Investment of ethanol-1 and ethanol-2 was R 34.08 million. There were differences in the factors that were used between paper 1 and paper 2. In terms of the capital investment cost, these included the location factors, and the CEPCI (time-adjustment factor). Additionally, there was a slight adjustment in the production capacity (48 kt/a vs 47 kt/a), and most importantly, the exchange rate was higher in 2016 (paper 1). One would think that the capital investment in paper 1 would be reasonably higher than that in paper 2, however, in comparison to the difference in the Total Production Costs, these changes did not have a substantial effect. It is more likely that the factors which were applied to the FCI in the TPC calculation had a more substantial impact than the FCI alone.

The values that were used for the selling prices in both papers were comparable. The project lifetime was also extended in ethanol-2. Whilst the extended project lifetime would essentially increase the NPV, a difference of 5 years would not have had such a substantial effect on the difference in the NPV. The NPV after 20 years in ethanol-2 was R 804 million while the NPV after 25 years was R 846 million. The total production costs were also inflated in the discounted cash flow of ethanol-1 and ethanol-2. A high total production cost would affect the NPV. This analysis demonstrated the importance of assumptions and their impact on the outcome of the feasibility calculation. Specifically, significantly different feasibility outcomes were obtained for the same product in the two papers because of the different assumptions that were used.

The question that required an answer from S-BEAT was how one would rank which products to send to the conceptual design stage? Additionally, when would the additional resources required for a detailed mass and energy balance of a specific integrated biorefinery concept be justified? It would be up to the individual company to decide what the limiting factor in their decision-making process is. If access to capital investment was of no concern, then a more comprehensive range of projects could be selected. If risky markets and risky behaviour of market players were of concern, then drop-in products which would compete with their mature petroleum counterparts might not be considered. If entry into new markets was not the primary concern, then dedicated bio-products might be the way to go. Ultimately many factors should be considered, however, the decision should be made in line with the company's objectives.

The results of the overall feasibility chart that was presented in paper 2 answers the question of how S-BEAT would aid in the ranking of biorefinery products. The following scenarios result from the overall feasibility chart:

Scenario A, the quickest payback period is preferred. Under this scenario, the products would proceed to the conceptual design in the following order, from first to last:

- When CJ is the starting material, ethanol > 1,4-BDO
- When syrup is the starting material, lactic acid > lysine-syrup > PLA
- The remaining four products can be considered next. However, close attention should be paid to the uncertainties in the market prices and the feedstock costs as well as the capital investment calculation.
 - When CJ is the starting material, MEG > SA
 - When syrup is the starting material, FDCA
- If lysine is to be considered, then it should first be considered from syrup and then from molasses (double capacity)

Scenario B, the highest NPV, is preferred. Under this scenario, the products would be ordered as follows:

- When CJ is the starting material, 1,4-BDO > ethanol > SA > MEG
- When syrup is the starting material, lactic acid > lysine > PLA > FDCA- syrup.

Of course, capital investments should also be considered together with the market potential when determining the best candidates for the conceptual design. If capacities are not suited for the global demand, but there is growth potential, then a lower risk co-product could be considered together with the main product.

The user would need to decide how much confidence they could place in the assumptions and references data that was used in the assessment when considering the outputs. If deemed appropriate, additional resources could be expended in obtaining improved reference data to decrease uncertainty in these outputs before progressing to economic feasibility studies based on detailed mass and energy balances.

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CHAPTER 5: OVERVIEW OF S-BEAT FEATURES

5.1 Structure of S-BEAT

The aims and objectives of this work played an integral role in the development of S-BEAT and can be found in Sections 1.3 and 2.6. S-BEAT was developed as a Microsoft Excel workbook which made use of cell formulas, Visual Basic for Applications (VBA) programming of user forms and Macros. Microsoft Excel is a well-known application which most users are able to access and use. The tool was developed with the end-user in mind. Checkboxes, option buttons, sliders, drop-down lists, and input boxes were extensively used to constrain the user's interactions with the spreadsheet formula. However, it was deemed too restrictive to limit the user to default values only, and many user-specific input values were allowed.

S-BEAT follows a systematic approach to obtain values for the plant capacity, capital and operating expenditure, Net Present Value, Internal Rate of Return, and the payback period of a product. Each major calculation step is done in a separate worksheet in S-BEAT. These sheets are *Design Specs*, *Literature Specs*, *CAPEX*, *OPEX*, *Economics*, *Scenario Analysis*, *Sensitivity Analysis*, *Results* and *Minimum Selling Price Seeker*. Pseudocode diagrams are used to represent the structure of each worksheet visually and give the user a deeper understanding of the capabilities of S-BEAT. Additionally, a step-by-step user manual is provided in Appendix B, with images of S-BEAT itself.

5.1.1 The Design Specifications sheet

In order to successfully use S-BEAT and consequently, the *Design Specifications* sheet, the following questions require answering:

1. What product is to be evaluated, and can this product be produced from a sucrose-based feed stream?
2. Suppose the raw material stream for the new downstream biorefinery plant is obtained from a sugar mill. Will the new plant be constrained to operating during the crushing season of the sugar mill? How many hours in the day will the plant be operational?
3. What percentage of the sugar mill feed stream will need to be diverted to the biorefinery to obtain a feasible production capacity?
4. Will the raw material be processed to one, two or three products, and is the necessary information for each product available?
5. What reactions are required to obtain the final product from the raw material stream and are reactor conversions and separation recoveries available for this?

The structure of the *Design Specifications* sheet is shown in Figure 5.1 and Figure 5.2. S-BEAT has default values for sugar mill stream compositions, flowrates, and stream costs. User-specified values can replace these default values. The plant operational days and hours, as well as the plant capacity, are required. Often the production capacity that results in a feasible plant is unknown, and this is one of the factors that S-BEAT varies in the *Sensitivity Analysis* sheet. Different production capacities can be assessed in the *Design Specifications* sheet by adjusting the percentage of the raw material feed stream that is diverted to the biorefinery.

The first notable feature of S-BEAT is that it allows for up to three different products to be processed. Each product in the processing route is the feed material to the next stage in the process. This feature was used in multiple case studies in Chapters 3 and 4. For example, consider the analysis of a monoethylene glycol (MEG) plant that follows the processing route of raw material to ethanol to ethylene to MEG. S-BEAT would consider ethanol to be the initial product, ethylene would be the intermediate product, and MEG would be the final product. Additionally, S-BEAT allows for up to three reactions per product. For example, ethylene may see up to three reactions before it is converted to MEG. A radio-button aids with the selection of the number of reactions, the user must select either one, two or three reactions before the reactions are entered.

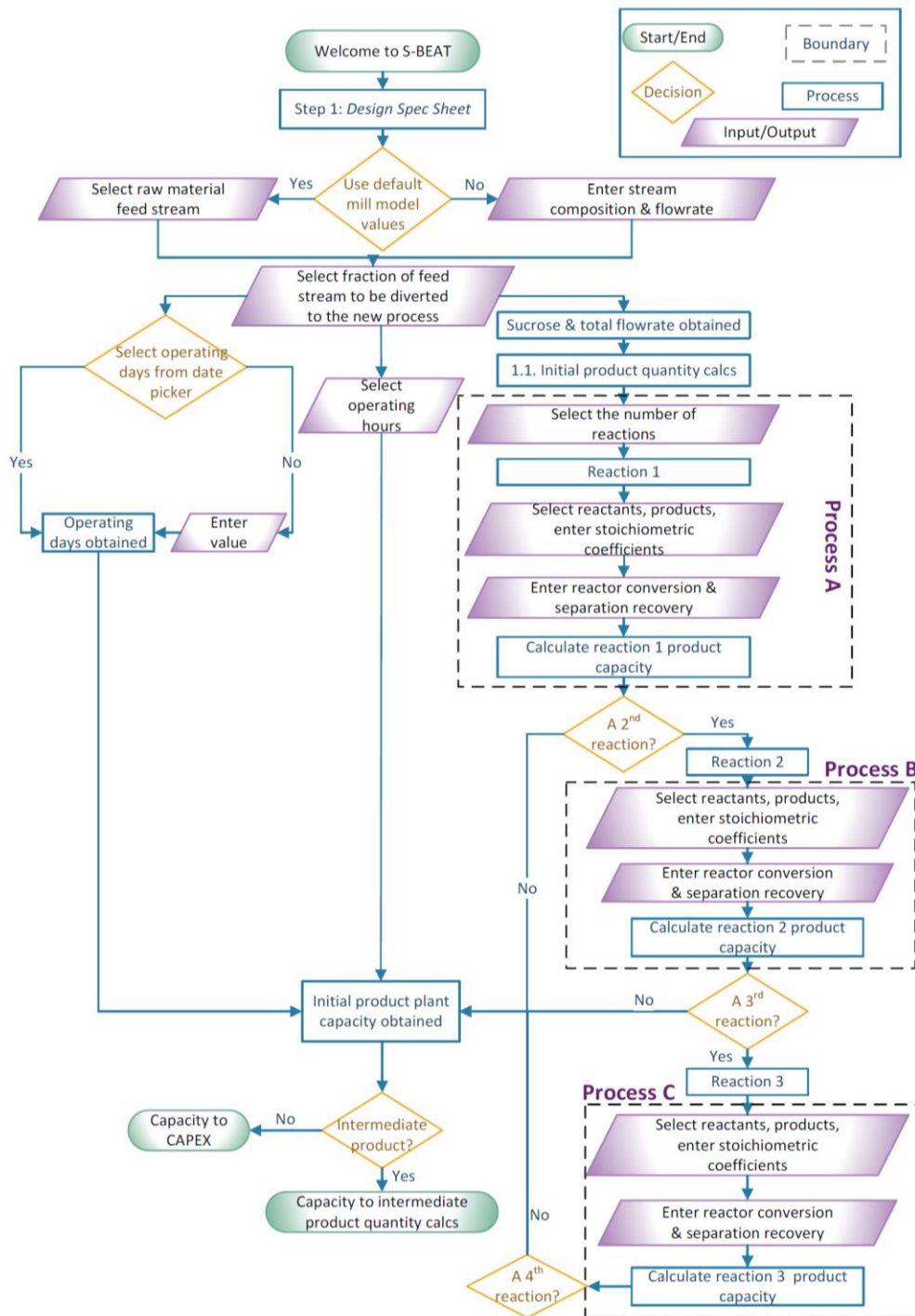


Figure 5.1: Pseudocode diagram of the initial product analysis in the Design Specifications sheet.

S-BEAT has a comprehensive system for entering the reaction stoichiometry. The first reactant is selected, and a button is clicked, which calls on a library of chemicals with their chemical formula and molecular weights. The reactant can be searched for by either the name or the formula. When the reactant is found, it is selected, and the library is closed. The reactant is populated to the required position in the *Design Specifications* sheet and the stoichiometric coefficient of the reactant can then be entered in the designated cells. This process is repeated for

each reactant and product. The product capacity of the reaction results after the reactor conversion and separation recoveries are entered. Suppose a process contains more than one product. In that case, the initial product information can be entered from beginning to end (*Design Specifications to Economics*), before returning to the *Design Specifications* sheet to enter the following products information. Alternately, each product can be entered simultaneously from beginning to end. The key is to remember that the capacity of each product feeds into the next product capacity calculation, i.e., the initial product must be entered before the intermediate product can be assessed and so forth.

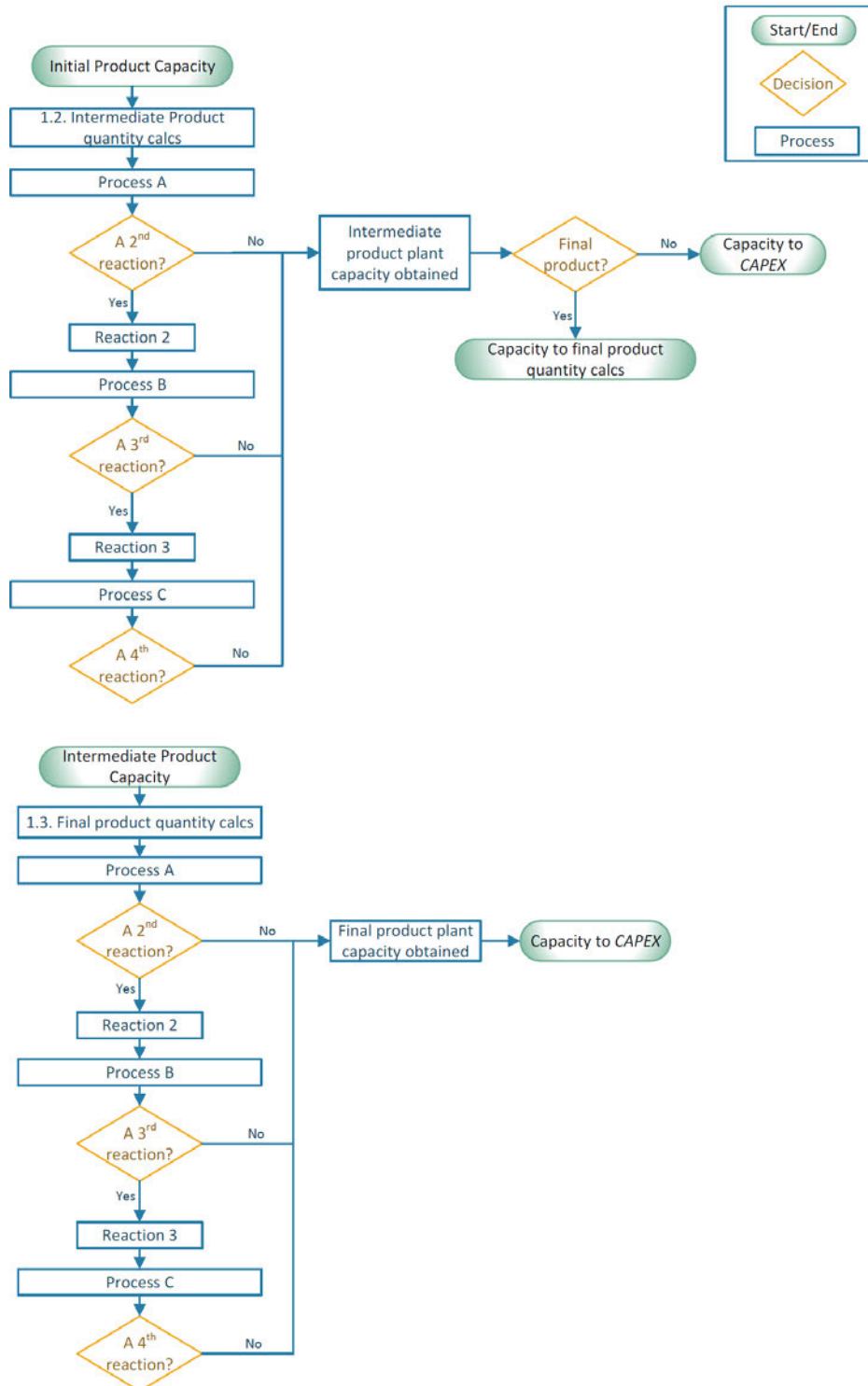


Figure 5.2: Pseudocode diagram for the analysis of the intermediate and final product sections in the Design Specifications sheet

5.1.2 The Literature Specifications sheet

S-BEAT employs the order-of-magnitude method, and data from a reference plant is required to obtain the capital and operational costs for the biorefinery of interest. Information of a historical processing plant or literature data, which is similar to the new plant that is being analysed is a

necessity. This information includes the year of construction and location of the reference plant together with the plant capacity and capital investment. The structure of the *Literature Specifications* sheet can be seen in Figure 5.3. The structure and logic remain the same for the initial product section, intermediate product section and the final product section.

South Africa was pre-specified as the new plant location as per the objectives of this work. Until biorefineries become a staple of the South African economy, it will be impossible to find reference plants that were built in South Africa. A location factor was, therefore, necessary for S-BEAT to relate the costs associated with the historical plant location to the new location. Intratec Solutions (2013) describe their location factor as being comprised of labour costs, productivity, equipment import requirements, local steel prices, taxes, freight, and duties on domestic and imported materials, local business environments and local availability of equipment. They group these properties into the following categories: business environment, infrastructure, labour and materials (Intratec Solutions, 2013). Location factor information, like the Intratec Location Factor, usually needs to be purchased. A decision was taken to use an index which is available on the public domain and was representative of a country's business environment, infrastructure, labour and materials for a location factor in S-BEAT.

The representative location factors that were selected for the default location factor library were the Deloitte 2016 Global Manufacturing Competitiveness Index (Deloitte Touche Tohmatsu Limited, 2016) and the 2018 World Economic Forum Global Competitiveness Index (Schwab, 2018). The different libraries were included, as tables in S-BEAT and they can be accessed with radio button selections and drop-down buttons, to accommodate the different design years that were used in the case studies found in Chapters 3 and 4.

The 2016 Global Manufacturing Competitiveness Index was selected as the representative location factor in S-BEAT. This index was constructed by analysing surveys that were undertaken by global CEOs in manufacturing. They were questioned on topics which included business confidence, the 2016 business environment, manufacturing competitiveness and demographics. They were subject to questions on the global economic environment at an industry and country level, skill shortages, concerns about including new products and services, and their opinions on government policies and regulations (Deloitte Touche Tohmatsu Limited, 2016). The results of the survey were weighted, and the index was constructed.

The 2018 World Economic Forum Global Competitiveness Index contained 98 distinct factors which determined the productivity of a country. Those factors were grouped into four categories:

Enabling environment, human capital, markets, and innovation ecosystem (Schwab, 2018). The categories encapsulated the following: a country's security, public sector performance and corporate governance, the quality of transportation and utility infrastructure, the degree of information and communications technologies, the level of inflation, health-adjusted life expectancies, level of skills and quality of education, the countries market power and the degree of market distortions, human resources, the financial system, market sizes, adoption of new technologies and research and development (Schwab, 2018). Whilst this index exceeded the requirements for a plant location factor for S-BEAT, it was deemed a good representation of a country's productivity. In the literature, some authors accounted for location adjustments by increasing the FCI (Santos *et al.*, 2018). While other authors have used the Intratec Location Factors (Bressanin *et al.*, 2020), which are freely available online for the years 2000 to 2002, a paid subscription is required for more recent years.

It must be noted that the location factors are default values, and a user may enter values into S-BEAT if they have readily available location factors for both South Africa and the reference plant location.

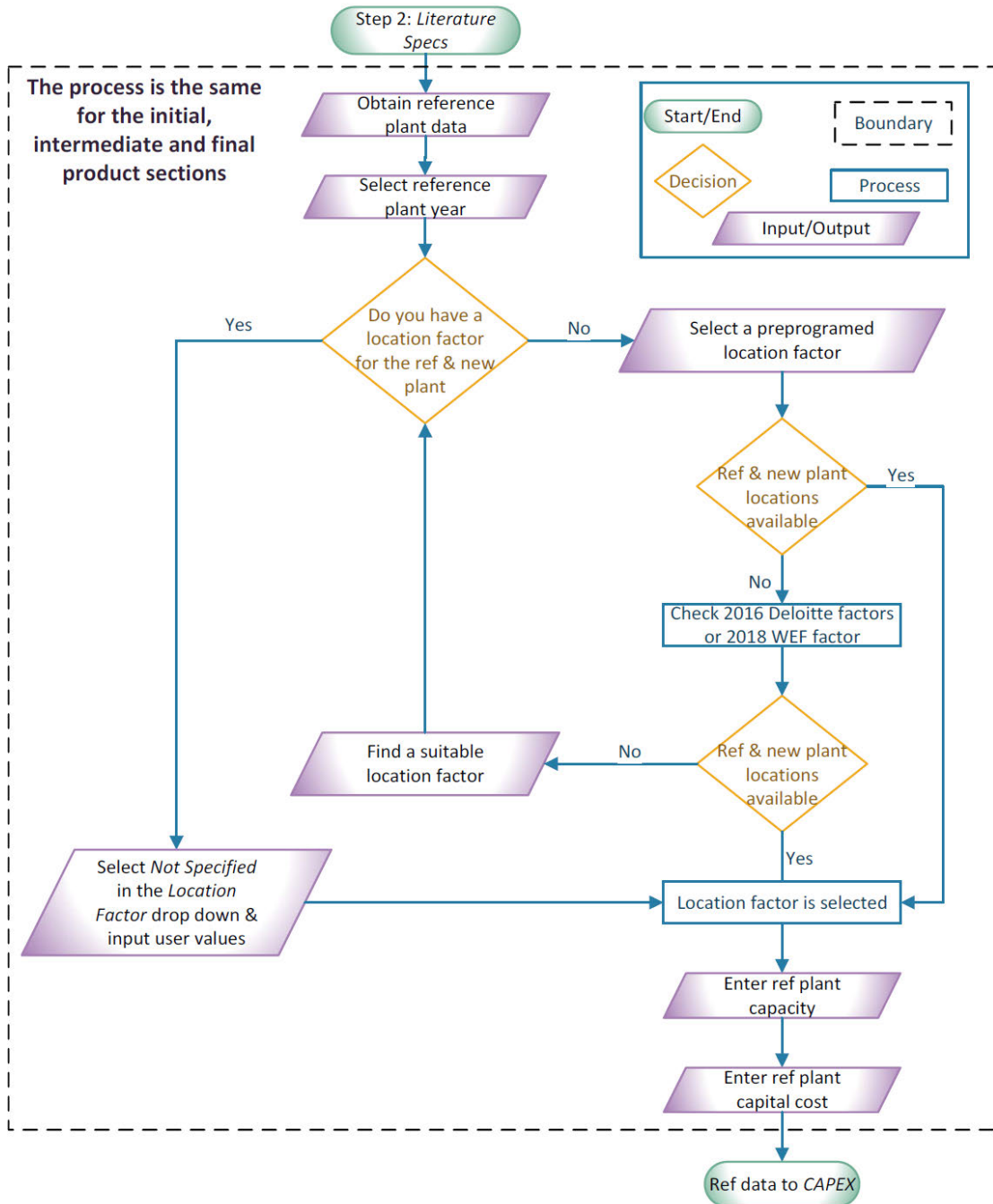


Figure 5.3: Pseudocode diagram of the Literature Specifications sheet in S-BEAT

5.1.3 The CAPEX sheet

It was previously mentioned that S-BEAT uses the order-of-magnitude approach to obtain the capital investment of a new plant from the investment of a similar existing plant. This calculation is possible provided the capacity of the new plant (output from *Design Specifications*) and reference plants (output from *Literature Specifications*), plant locations (output from *Literature Specifications*), construction years (input in *CAPEX*), and a cost-capacity scaling exponent (input in *CAPEX*) are known. The difference between the reference and new plant construction years is

accounted for by the CEPCI value, which is either updated manually or automatically by the default values. The cost-capacity scaling exponent can either be selected from a drop-down or manually entered.

For CAPEX estimates, nominal plant capacity is typically determined assuming 100%-time utilization. S-BEAT currently uses the product throughput in tonnes per hour and expected operating period in hours per year to determine the plant capacity in tonnes per year for the CAPEX calculations. For a plant that does not operate throughout the year, the current method will result in an underestimation that would need to be addressed in future versions of S-BEAT by applying a time utilisation factor to the annual throughput.

The *CAPEX* sheet determines whether the reference capital investment value (input in *Literature Specifications*) was a Total Capital Investment (TCI) or a Fixed Capital Investment (FCI). If 0% is entered for the reference Working Capital Investment (WCI), then it is understood that the capital investment value available was the FCI. The contingency factor, which can be manually adjusted using a slider, was provided to account for any discrepancies that may arise from the reference data like exclusions of vital costs. The capital investment gets converted from the reference plant currency to South African Rands at the end of the CAPEX calculation. The remainder of the assessment is conducted in Rands. The default currency values may be used, updated monthly, or updated when required. Figure 5.4 provides the pseudocode diagram for the *CAPEX* sheet. The logic is repeated for the initial, intermediate, and final product processes.

The order-of-magnitude method was selected to cater to the scope of the project. One of the main objectives of S-BEAT was to create a simple easy to use tool which would allow a user to conduct comparisons between the feasibility of different biorefinery products. Firstly, the amount of information that is required for a detailed study estimate is higher than that required to obtain an order-of-magnitude estimate. Suppose a study was to be conducted to compare ten different products, with each product having five possible processing routes. Additionally, the study wanted to analyse the pros and cons of using three different sucrose-containing raw material streams. This study would require multiple process flow diagrams with numerous material and energy balances. It may take months or years to complete, depending on the complexity of the scenarios under investigation. A possibility exists where the outcome of the study would suggest that only one scenario would be feasible. At this point, an incredible amount of time and resources would have been expended on this project.

S-BEAT was developed so that a platform could exist to obtain preliminary estimates of various scenarios, with many products and processes for comparative purposes. The scenarios would subsequently require a ranking process where the highest-ranked case could be promoted to undergo a more rigorous cost estimation method. For this purpose, a preliminary order-of-magnitude method is appropriate.

S-BEAT allows for numerous user inputs, which may affect the outcome of the economic assessment gravely if the user chose unrealistic or wrong values. Although this may be seen as a weakness of S-BEAT, the developer decided that a greater degree of user choice (with suitable default values) would increase the uptake of the tool in the industry. It became apparent in discussions with industry representatives that each company has its own set of in-house parameters on which they base their business case assessments. Hence, S-BEAT has pre-set default values which can easily be changed, if required. A further security measure was taken in the form of the *Sensitivity Analysis* sheet, which, amongst other reasons, allows a user to test the consequence of using inaccurate values in the study.

A user should bear in mind that using the reference information of a process that has a high Technology Readiness Level (TRL) would likely lead to result in more precise results than a process with a low TRL. Whilst most biorefineries may still be in the developmental or conceptual phases with low TRLs, the time cost of using S-BEAT to analyse a low TRL process for interest's sake would be low. The main takeaway should be that S-BEAT provides the platform for the calculations. However, the reliability of the S-BEAT output/predictions depends on the appropriateness of the user or default inputs for the particular analysis.

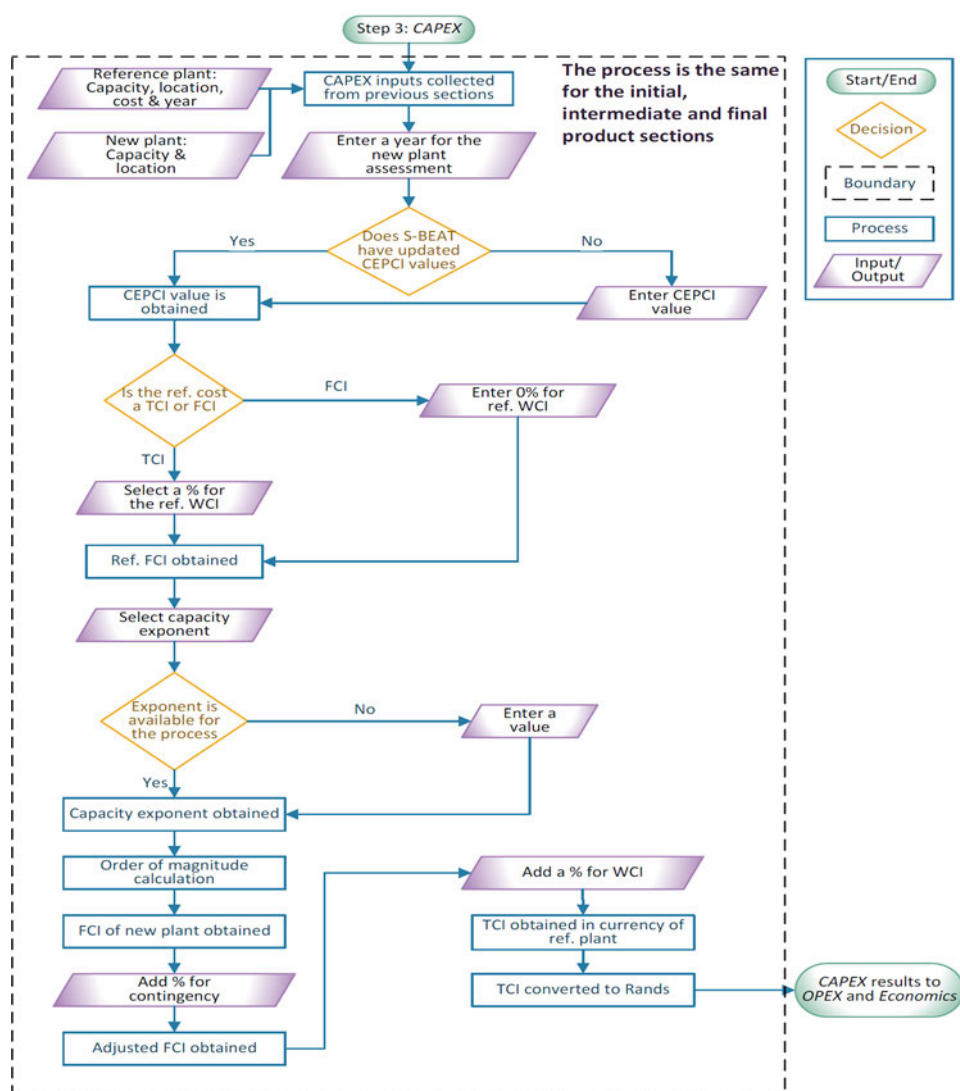


Figure 5.4: Pseudocode diagram of the CAPEX sheet in S-BEAT

5.1.4 The OPEX sheet

As with the previous sheets, the *OPEX* sheet has separate sections for the initial, intermediate, and final products. Figure 5.5 shows the pseudocode diagram of the *OPEX* section. The boundary separates where the process differs between the initial, intermediate, final product sections. The programming in S-BEAT assumes that if a process has multiple products, then every product is produced within the same biorefinery facility, even if the reference data was obtained from separate reference facilities. Double accounting of the raw material cost is avoided by entering said cost in the initial product section only. The default raw material stream costs may be used, or user-specified values may be entered.

An attempt was made to develop a cost for intermediate factory streams. It was found that the value of a stream to the sugar mill depends on mill specific design and operating conditions. Therefore, default values may poorly represent the stream value for specific mills. Furthermore,

industry members generally do not have a good feel for the value of a particular stream in a particular mill. Therefore, one of the key model parameters, the feedstock price, is inherently uncertain. The most recent version of S-BEAT, as of 2020, included a calculation of the minimum selling price (MSP) that was required to obtain a plant with an Internal Rate of Return (IRR) which was equal to the Minimum Acceptable Rate of Return (MARR). The MSP calculation was added to S-BEAT to replace the feedstock cost with a range and to determine the required minimum selling price that results in the $IRR = MARR$ for the feedstock range. This feature is explained in further detail in section 5.1.9.

The second OPEX calculation that requires user input is the operating labour calculation. S-BEAT has preprogrammed values for major operating equipment which can be selected from a list in a user input form. Each piece of equipment has a value associated with it for the number of operators required per unit. If a unit does not exist in the list, then user-specified equipment should be selected, and a value entered for it. Once the number of equipment units is entered, S-BEAT calculates the number of operators that are required and the operating labour cost. An additional calculation exists where salaries of other personnel on the plant may be specified, or one could assume that these costs fall within the plant overheads category in the OPEX calculation. The plant overheads factor should be reduced if management/overhead salaries are entered explicitly, the default factor assumes that the salaries are included in the calculation.

The Total Production Cost (TPC) of the plant is calculated by applying factors to the Fixed Capital Investment (FCI) as well as other costs that are associated with operational expenditure, like maintenance and operating labour. The details of the OPEX calculation were described in Chapter 3. User inputs are allowed for all the factors in the OPEX calculation. A factor which requires mentioning is the *Utility factor* which was included to allow for adjustments to the utility cost of the plant.

An integrated biorefinery produces a variety of products from biomass. The biorefinery employs various conversion technologies to optimise the production of chemicals, biofuels, animal feeds, heat, and power from said biomass. Whilst the efficient use of energy and careful integration of different processes within the biorefinery would reduce the production costs of a biorefinery, mass and energy balances were not included in the scope of this work. Hence, energy optimisation could not be incorporated. The utility factor is not a substitute for an energy balance. However, it is not useless. A user could vary the utility factor in a sensitivity analysis to postulate whether drastic increases in the utility costs, due to inefficient energy conversion processes, would cause a plant to become unfeasible. The lack of a material balance imposed another limitation on the

tool. This limitation was that the consumption of raw materials, other than sucrose, were not included. It was initially assumed that the cost of the sucrose-based feedstock would account for the majority of the raw material costs and as such other consumables were not included. A workaround to this should be included in future versions of S-BEAT, to test whether this hypothesis holds.

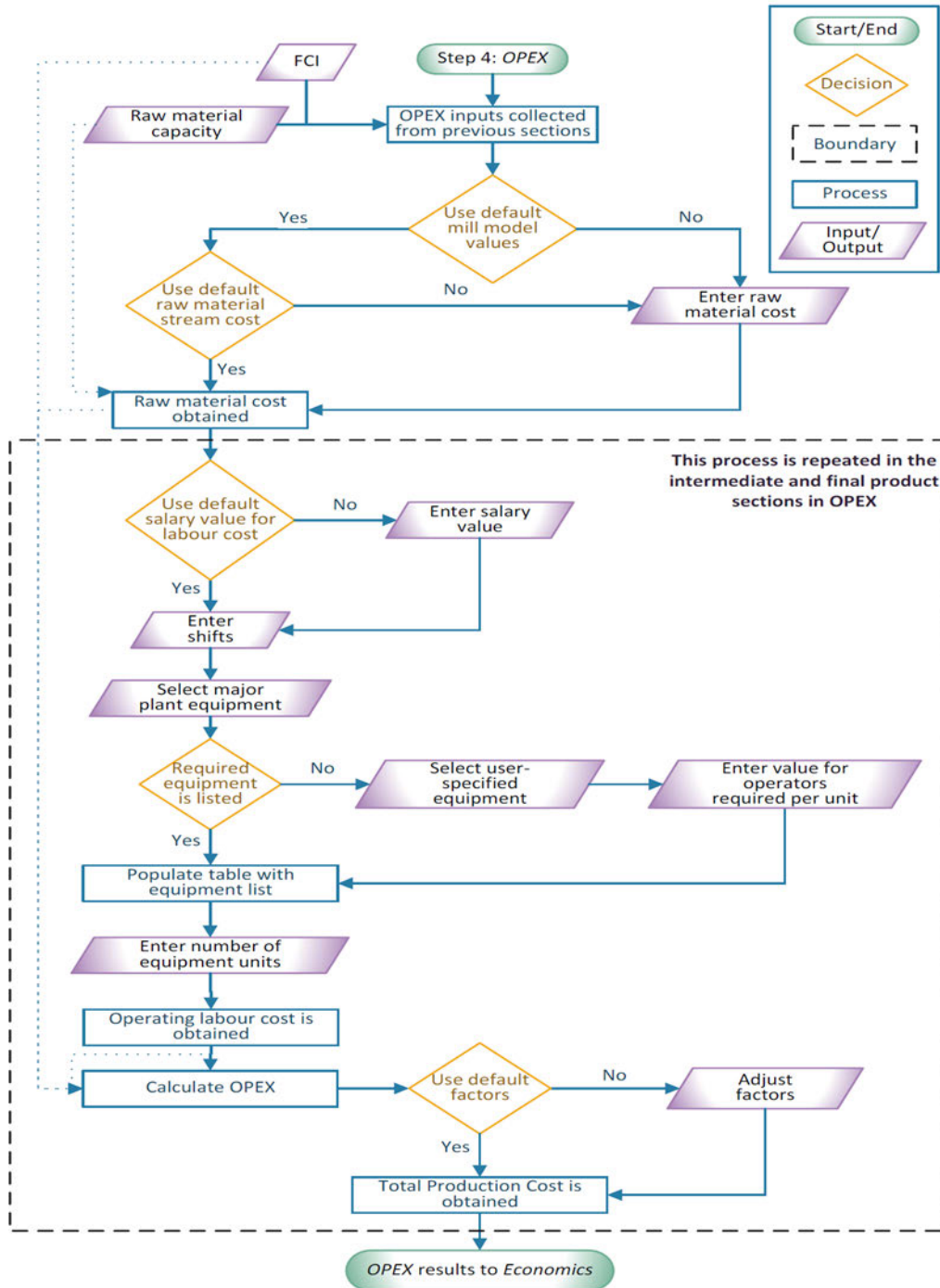


Figure 5.5: Pseudocode diagram of the OPEX section in S-BEAT

5.1.5 The Economics sheet

A Discounted Cash Flow (DCF) analysis was used to determine the feasibility of the different biorefinery processes, more specifically, the Net Present Value (NPV), Internal Rate of Return (IRR) and both simple and discounted Payback Periods (PBP). Whilst the previous sheets in S-BEAT have sections for the initial, intermediate, and final products. The *Economics* sheet does not. Radio buttons exist where the user can switch between the individual products. When the initial product button is selected, a selling price must be entered in the relevant place.

Additionally, S-BEAT retrieves the Fixed Capital Investment, Working Capital Investment, Total, Variable and Fixed Production Costs and populates them into their respective spots in the DCF. If the intermediate product button is selected, the selling price must be entered, and S-BEAT returns the sum of the initial and intermediate product FCI, WCI, TPC, FPC and VPC. Likewise, if the final product is selected, then the summation of the initial, intermediate, and final product FCI, WCI, TPC, VPC and FPC are returned.

It has been postulated that a significant benefit of a multiproduct biorefinery is that production can be diverted according to fluctuations in market demand and market prices. Whilst S-BEAT can evaluate a multiproduct biorefinery, the capability for partial diversion of either the initial or intermediate products has not been included. One of the reasons for this omission is that for a fixed plant capacity, varying production throughput would affect the operating expenses of the plant, specifically the variable production costs. S-BEAT has calculated the OPEX based on factors which are often based on the Fixed Capital Investment, the variable production costs could, however, be reduced by order-of-magnitude. Ultimately, a very detailed material and energy balance would provide the best basis for calculating the variable production costs and hence the effects that partial conversion of the initial/intermediate or a combination of the two, would have on the feasibility of the plant.

Default parameters can be used for the DCF, or values can be entered for the discount rate, tax rate and inflation of the selling price and total production cost. The inflation can be set to zero. Previous versions of S-BEAT applied the Modified Accelerated Cost Recovery System (MARC) to the depreciation calculation. However, the 2020 version of S-BEAT allows the user to toggle between the MARC method and the straight-line depreciation method. If the straight-line depreciation method is selected, then the depreciation period must be entered, and the depreciation rate is calculated and populates the table with a click of a button. Microsoft Excel table features allow the lifetime of the plant to be increased or decreased by changing the number of years of the assessment. In Chapter 4, the project lifetime was extended from 20 years (Chapter 2) to 25

years, and this was a project internal decision following discussions with industry representatives. Figure 5.6 shows the pseudocode diagram of the *Economics* and *Scenario Analysis* sheets in S-BEAT.

5.1.6 The Scenario Analysis sheet

The *Scenario Analysis* sheet is the heart of S-BEAT and is one of the most defining features. The purpose of this sheet was to allow a user to save any scenario that was conducted. The scenario can be saved by simply clicking the *save scenario* button, selecting whether to save the initial, intermediate, or final product and naming the scenario. The values of the 110 parameters in S-BEAT are then saved to the scenario analysis table. The scenario analysis table uses the Microsoft Excel table functionality and a VBA script. Column one has the names of all the parameters that are to be saved when a new scenario is named. A new column gets added to the table, and the column header takes the name of the scenario. The algorithm records whether the initial, intermediate, or final product button was selected, the programme then checks each row in the parameter column, matches the parameter name to the corresponding name in S-BEAT and populates the table with the required values. An example of a saved scenario can be seen in Figure 5.7. The saved scenarios are useful for referencing values that were used in previous case studies. However, the power of saving scenarios becomes apparent when it is explained in conjunction with the *Sensitivity Analysis* sheet, and S-BEAT's automatic graphing in the *Results* sheet.

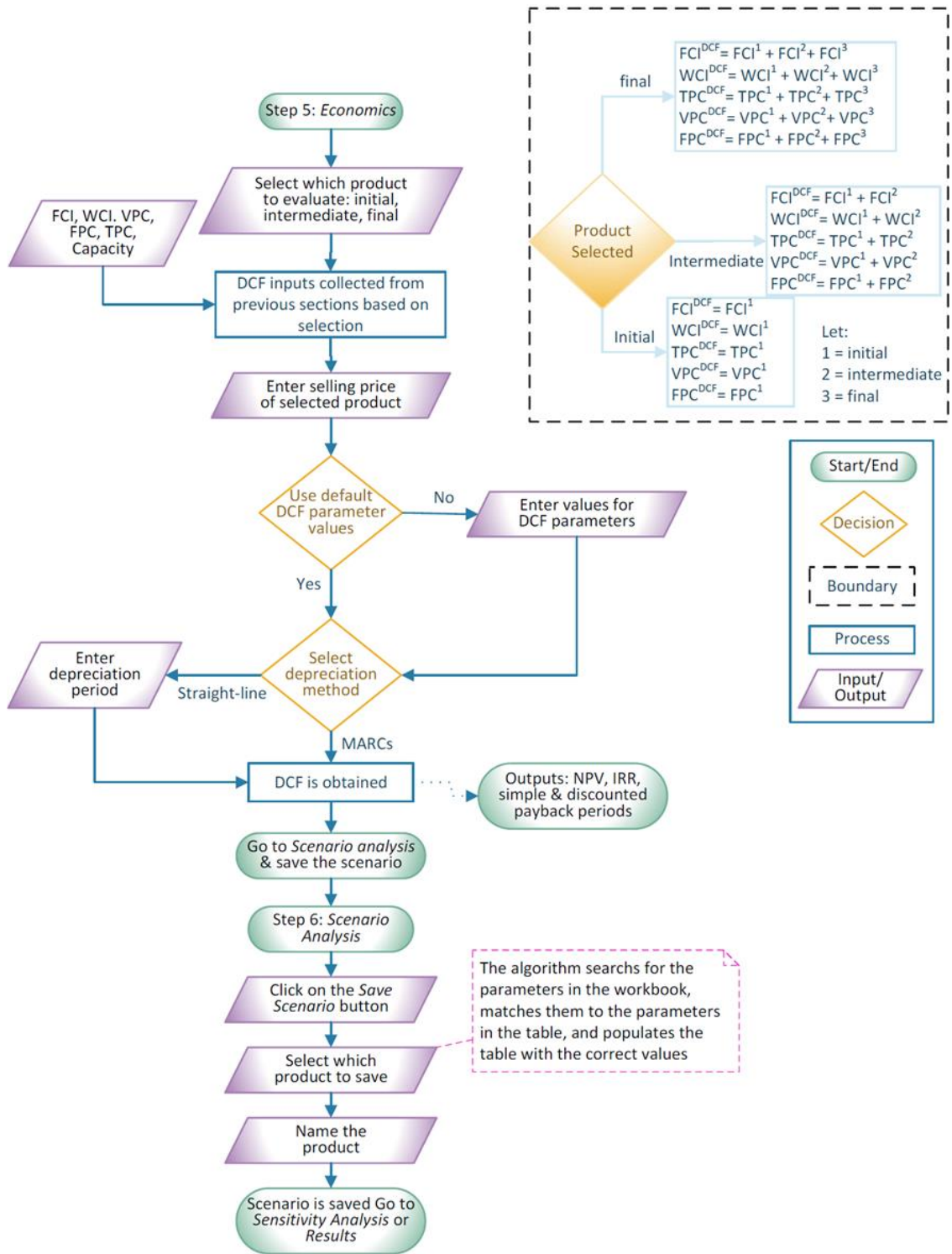


Figure 5.6: Pseudocode of the Economics sheet and the Scenario Analysis sheet in S-BEAT

Save Scenario	
Parameters	Succinic Acid Hig
Case Study	
Product Number	
Feed Source:	Sugarcane
Mill Model:	Yes
Stream Name:	Clear Juice
Season Start:	2016/03/30
Season End:	2016/12/07
Plant Operational Hours	24.00
Main Reaction	$7 \text{ C}_6\text{H}_{12}\text{O}_6 + 6 \text{ CO}_2$
Reactor Conversion	94.00
Separation Recovery	95.00
Product Quantity tph	17.07
Data Source:	Literature Process De
Data Reference:	Intratec Solutions
Plant Product:	Succinic Acid
Designing a Similar Plant:	Yes
Ref Plant Year:	2014.00
Ref Plant Location:	United States
Ref Product Capacity:	77000.00
Ref Plant Capital Cost:	260000000.00
New Plant Year	2019.00
New Plant Location	South Africa
User Location Factor	1.40
User SA Location Factor	1.20
Location Factor	0.60

Figure 5.7: Example of the Scenario Analysis table

5.1.7 The Sensitivity Analysis sheet

The sensitivity analysis feature in S-BEAT allows the user to test the effect of changing different variables. There are sections for initial, intermediate, and final products, and the same variables can be changed independently for each product. However, the initial product section has additional variables. For simplicity, adjustments to variables in the *Economics* sheet are all made in the initial product section. However, changes are made no matter which product is selected in the *Economics* sheet. The following specified variables can be changed:

1. In the Design Specification sheet:

A fraction of the feed mill stream that is diverted to the biorefinery (value is entered in the initial product section only), operating days (value is entered in the initial product section only), reactor conversion, separation recovery, product quantity

2. In the Literature Specifications sheet:

The plant location factor

3. In the CAPEX sheet:

CEPCI, working capital factor, contingency factor, FCI

4. In the OPEX sheet:

Raw material cost (value is entered in the initial product section only), number of equipment operators, total operating labour salary, salaries, direct production cost, fixed production cost, the utility factor

5. In the Economics sheet (values are entered in the initial product section only)

Selling price inflation rates, Total Production Cost inflation rate, MARR, selling price

Figure 5.8 shows the pseudocode diagram for the Sensitivity Analysis sheet

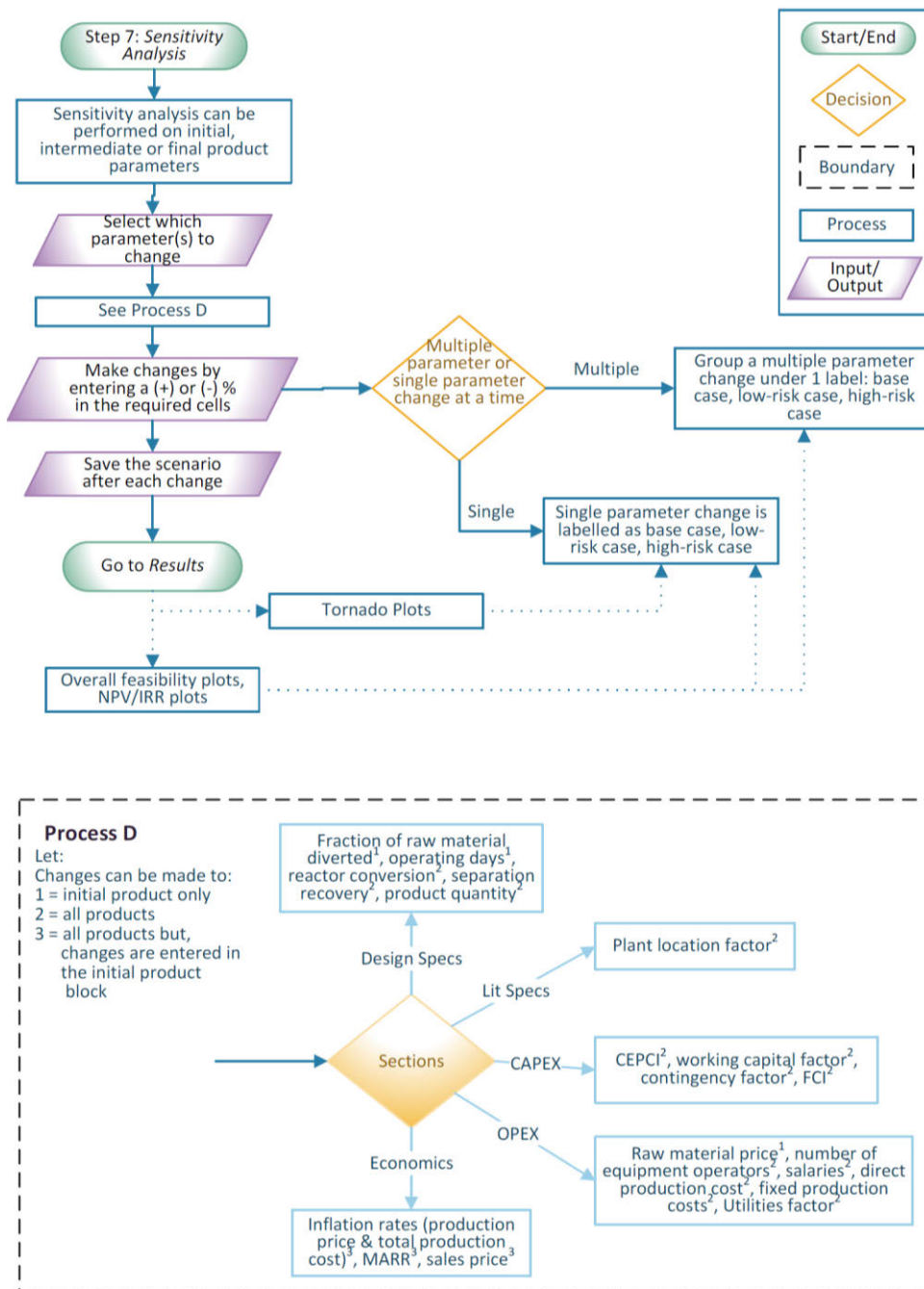


Figure 5.8: A pseudocode diagram of the Sensitivity Analysis sheet in S-BEAT

A positive or negative percentage must be entered into the block, which corresponds to the parameter the user wants to vary. The power of the *Scenario Analysis* feature lies in its interaction with the *Sensitivity Analysis* sheet and the graphing capabilities found in the *Results* sheet. The scenarios should be saved after each change that is made in the *Sensitivity Analysis* sheet. S-BEAT allows the user to vary one parameter at a time or multiple parameters that are grouped. S-BEAT uses the following terms when performing a sensitivity analysis:

- The Base Case refers to the scenario that was saved before a sensitivity analysis was performed.
- When one parameter is varied at a time, the low-risk case refers to the parameter which improves the feasibility of the process. For example, increasing the selling price would increase the annual sale revenue and hence be the low-risk case. Also, if the fixed capital investment were to be decreased, it would be a low-risk case.
- Alternatively, a high-risk case would refer to a change in a parameter that would decrease the feasibility of the process. For example, decreasing the selling price would decrease the annual sale revenue and hence be a high-risk case.
- Suppose multiple parameters are varied at a time. In that case, a low-risk case could refer to a scenario where the selling price was increased whilst the fixed capital investment and the raw material cost was decreased. The opposite is true for the high-risk case. A high-risk case would decrease the selling price whilst increasing the fixed capital investment and raw material cost.
- The low-risk case can also be referred to as the minimum-risk case (abbrev. min)
- The high-risk case can also be referred to as the maximum-risk case (abbrev. max)

The reasons behind why the *Scenario Analysis*, *Sensitivity Analysis* and *Results* sheets should be explained in combination with each other become apparent in Figure 5.9 to Figure 5.15 and are elaborated on in the *Results* sheet section.

5.1.8 The Results sheet

The numerous graphs that were presented in Chapter 3 and Chapter 4 are automatically generated in the *Results* sheet in S-BEAT. However, before the different graphs are generated, the scenarios need to be run and saved. Drop-down lists allow the user to pick which scenario they want to appear in the different plots. Some plots require a sensitivity analysis to be done before the results are visualised.

A product summary overview of a selected product can be found in the *Results* sheet together with a plot of the NPV, or IRR or both the NPV and IRR can be represented for the base case scenarios. NPV and IRR plots are also produced for viewing the results of the sensitivity analysis. Tornado plots are made to determine which variable plays the most significant role in deviations to the NPV. Lastly, an overall feasibility chart (a bubble plot), which shows whether a product is feasible based on the sensitivity analysis results and the product's bubble position in the chart is obtainable. The overall feasibility plot is used to rank which products should be sent to a detailed study estimation calculation first for further investigations.

S-BEAT was built to allow for comparisons between different biorefinery products, and these comparisons can occur in different ways.

Three levels of comparisons exist in S-BEAT. They can be categorised with terminology that is associated with inheritance in object-orientated programming, i.e., “parent,” “child” and “sibling” classes (Sanchez and Carlton, 2002). The “child” and the “sibling” categories inherit the properties of the “parent” category. Figure 5.9 shows four scenarios and each product that is analysed requires the scenario to be saved in the *Scenario Analysis* sheet before the results are comparable. Scenario 1 and 2: The economic indicators of two different products which start from the same raw material can be compared. Scenario 3 and 4: The economic indicators of the same product, which starts from different raw materials, can be compared. Scenarios 1 to 4 are the simplest forms of analysis that can be performed in S-BEAT.

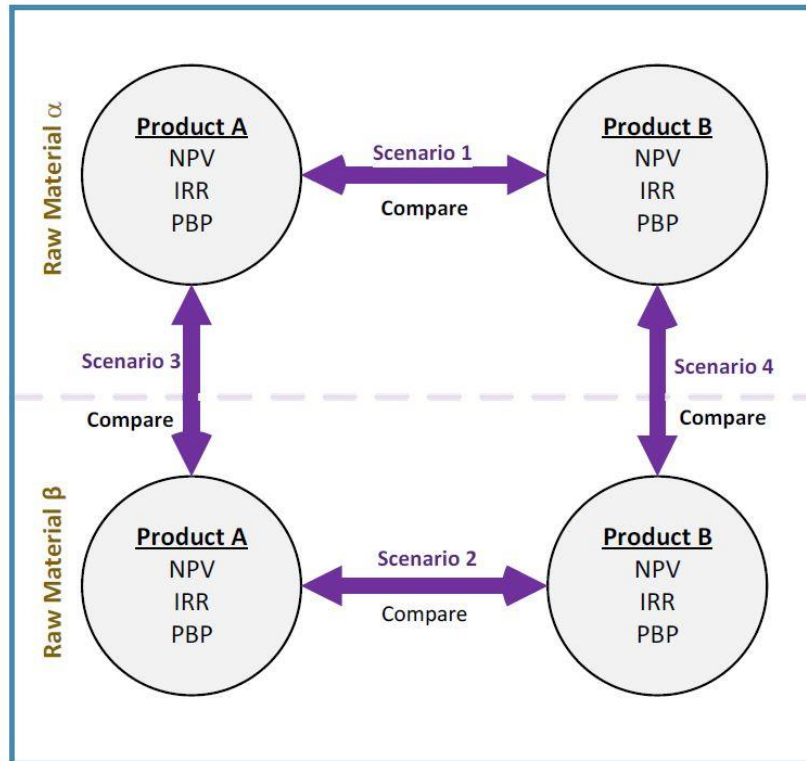


Figure 5.9: Depiction of the simplest form of comparisons between products in S-BEAT

Figure 5.10 shows a depiction of three saved scenarios. Scenario 5 compares the economic indicators of the same final product, which started from the same raw material stream but followed two different processing routes. Either different conversion technologies were used, or the intermediate products in the processing route differed. Scenario 6 compares Product B to Product A, both products started from the same raw material stream, and Product A was obtained through processing route γ . Scenario 7 shows that Product B can also be compared to Product A, which was obtained through processing route δ . Figure 5.9 and Figure 5.10 fall under the “parent” category of comparisons. The properties of Scenarios 1 through to 7 propagates to the “child” and “sibling” categories.

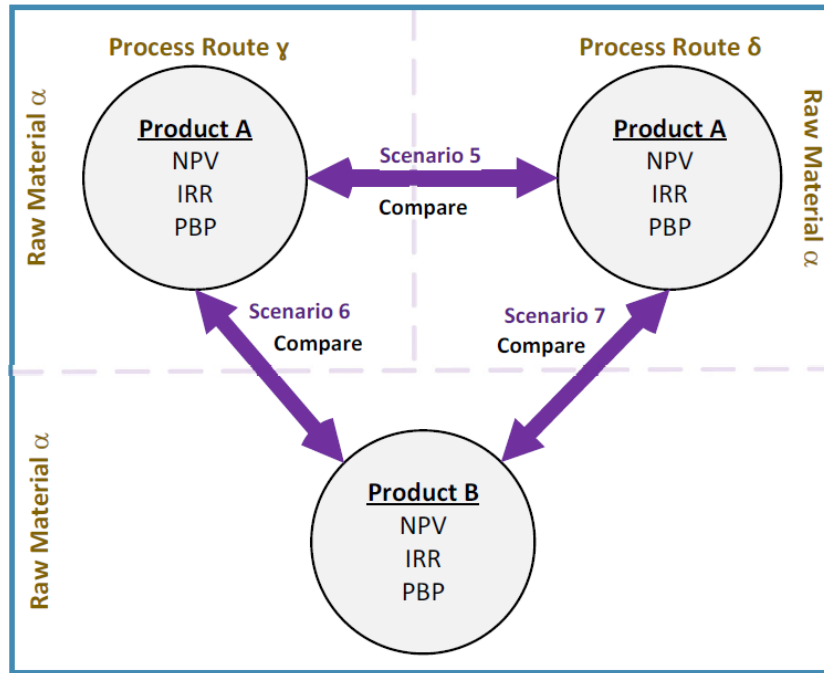


Figure 5.10: Comparing the economic indicators of different processing routes in S-BEAT

Figure 5.11 and Figure 5.12 depicts a “child” category of comparisons. This means that whatever scenarios were described by the “parent” category apply to these scenarios as well. Figure 5.11 shows a final Product A, which was obtained by processing route: Raw Material α \rightarrow Product A1 \rightarrow Product A2 \rightarrow Product A3 (Product A, the final product). When each product has been evaluated and saved, the following scenarios can be compared. Scenario 8: The economic indicators between Product A1 and A2 are comparable. This scenario shows the difference between ending at Product A1 or Product A2 in the process route. Scenario 9: The economic indicators between Product A2 and Product A3 are comparable. Scenario 10: The economic indicators between Product A1 and Product A3 are comparable. By comparing each product in the process route to each other, they are essentially viewed as if they were produced at different processing plants. However, they were calculated on the same basis and hence can be compared confidently.

Figure 5.12 shows a final Product B which was obtained by processing route: Raw Material α \rightarrow Product B1 \rightarrow Product B2 (Product B, the final product). Scenario 11 shows that even if the processing route had only two products, the economic indicators between Product B1 and Product B2 could be compared. Due to the inherited properties, a combination of scenarios can be generated and compared between Products A, B, A1, A2, A3, B1 and B2.

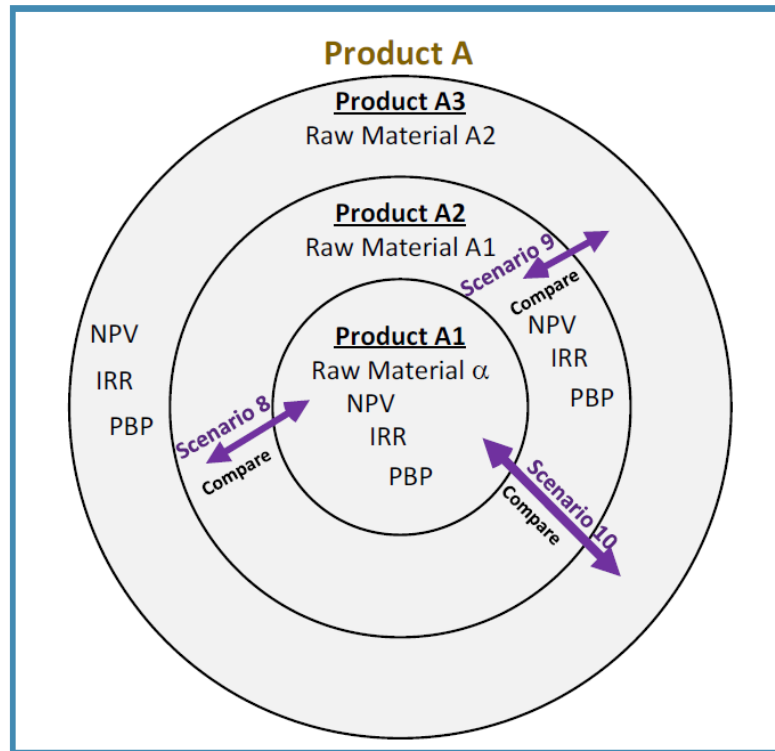


Figure 5.11: Scenarios in the “child” category of comparisons for products which have three different processes in the processing route

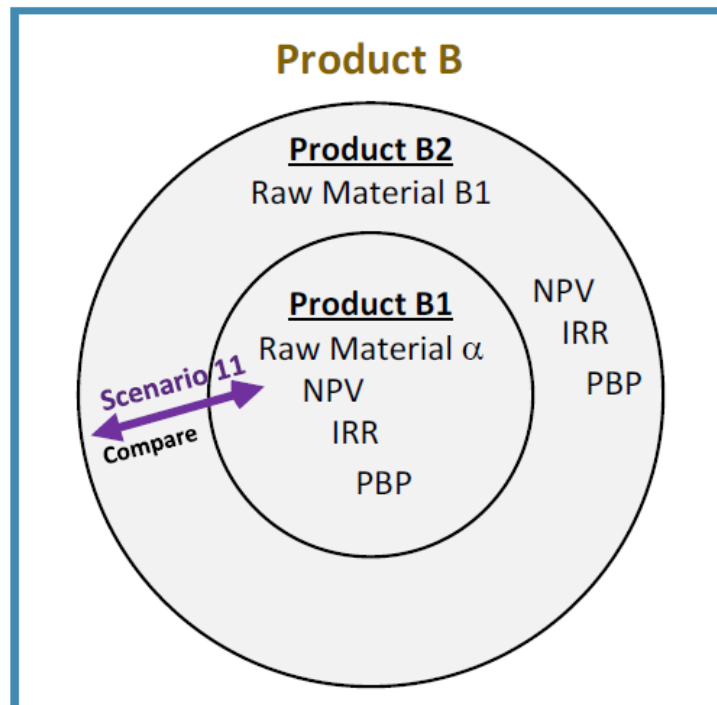


Figure 5.12: Scenarios in the “child” category of comparisons for products which have two different processes in the processing route

The third level of comparisons, the “sibling” category is described in Figure 5.13 and Figure 5.14. Product B, which has two products in the processing route, is used for the demonstration. The

“sibling” category essentially depicts that the results of the sensitivity analysis can be compared to one another. Scenario 12: The economic indicators of a multiple parameter sensitivity analysis can be compared between Product B1 and Product B2. This scenario is used for the overall feasibility charts as well as the NPV/IRR graphs in *Results*.

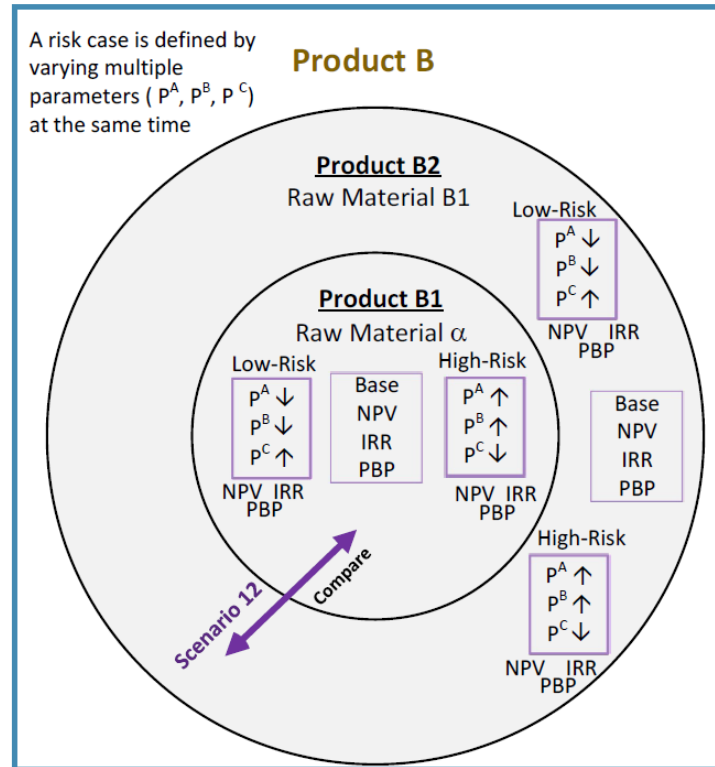


Figure 5.13: Multiparameter sensitivity analysis comparisons of the economic indicators

Scenario 13 in Figure 5.14 shows that results of varying one parameter at a time in the sensitivity analysis can be compared. The approach is generally used to obtain a Tornado plot as it shows which parameter when varied, has the most significant effect on deviations to the NPV of the product. Scenarios of this type are also used to output NPV/IRR plots and overall feasibility plots.

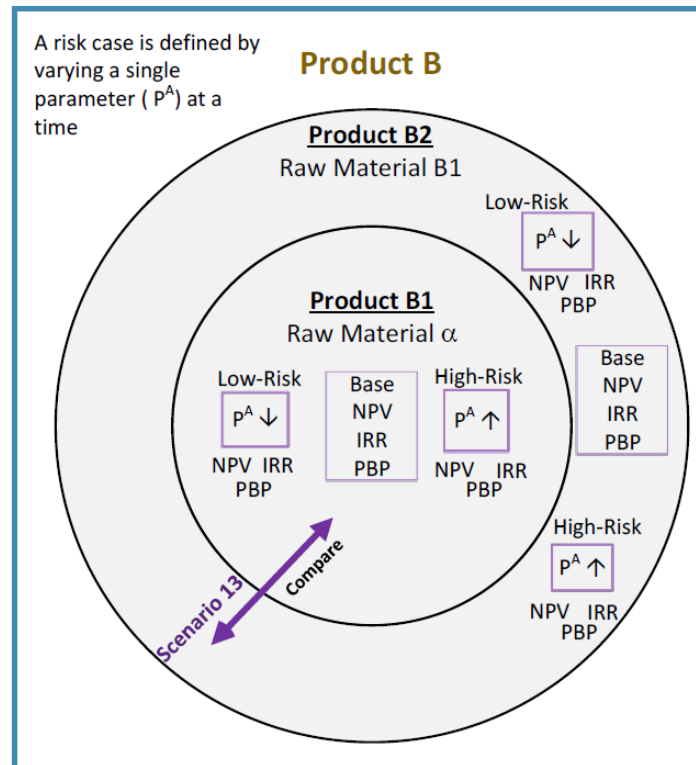


Figure 5.14: Economic indicators resulting from single-parameter sensitivity analysis can also be used for comparisons

Figure 5.15 presents a summary of some scenarios that were previously mentioned and the graphs that can be generated from them in the *Results* sheet. The overall feasibility plot is a bubble plot which is obtained by varying either single or multiple parameters in the sensitivity analysis. In the *Results* sheet, the user can select which scenarios to assess. A name is required for the product, followed by a selection of the *base case*, *low-risk case*, *high-risk case* scenarios from a drop-down (These are saved scenarios in the *Sensitivity Analysis* sheet). The code returns the NPV, IRR, and PBP for those scenarios. The NPV or IRR can be selected as the feasibility criteria. Once the feasibility criteria are selected, the algorithm looks at the *low-risk*, *base*, *high-risk cases* individually. The code labels the scenarios as either “Yes” or “No” depending on whether the criteria $NPV > 0$ or $IRR > MARR$ is satisfied. “Yes” represents a feasible case, whilst “No” represents an unfeasible case. The next step determines the colour of the bubble for the product on the chart. If all three cases are feasible, then the bubble colour is green. If the high-risk case is the only unfeasible case, then the bubble is orange, if the low-risk case is the only feasible case, then the bubble is yellow, and if all three cases are unfeasible, then the bubble is red.

The bubble chart automatically populates the product bubbles, the x-axis has the payback period whilst the y-axis has the parameter for which the feasibility criteria was analysed. A product can be ranked by their position on the chart. A product which has a position of the highest NPV (or

IRR) and the shortest payback period receive the highest rank. If there is a conflict in the bubble positions, then the bubble colours should be considered. A green bubble should take precedence over an orange bubble. The overall feasibility plots are one of the more interesting graphs that S-BEAT generates.

Process I. Raw Material $\alpha \rightarrow$ Product A1
 Process II. Raw Material $\alpha \rightarrow$ Product A1 \rightarrow Product A2
 Process III. Raw Material $\alpha \rightarrow$ Product A1 \rightarrow Product A2 \rightarrow Product A3

Process IV. Raw Material $\alpha \rightarrow$ Product B1
 Process V. Raw Material $\alpha \rightarrow$ Product B1 \rightarrow Product B2

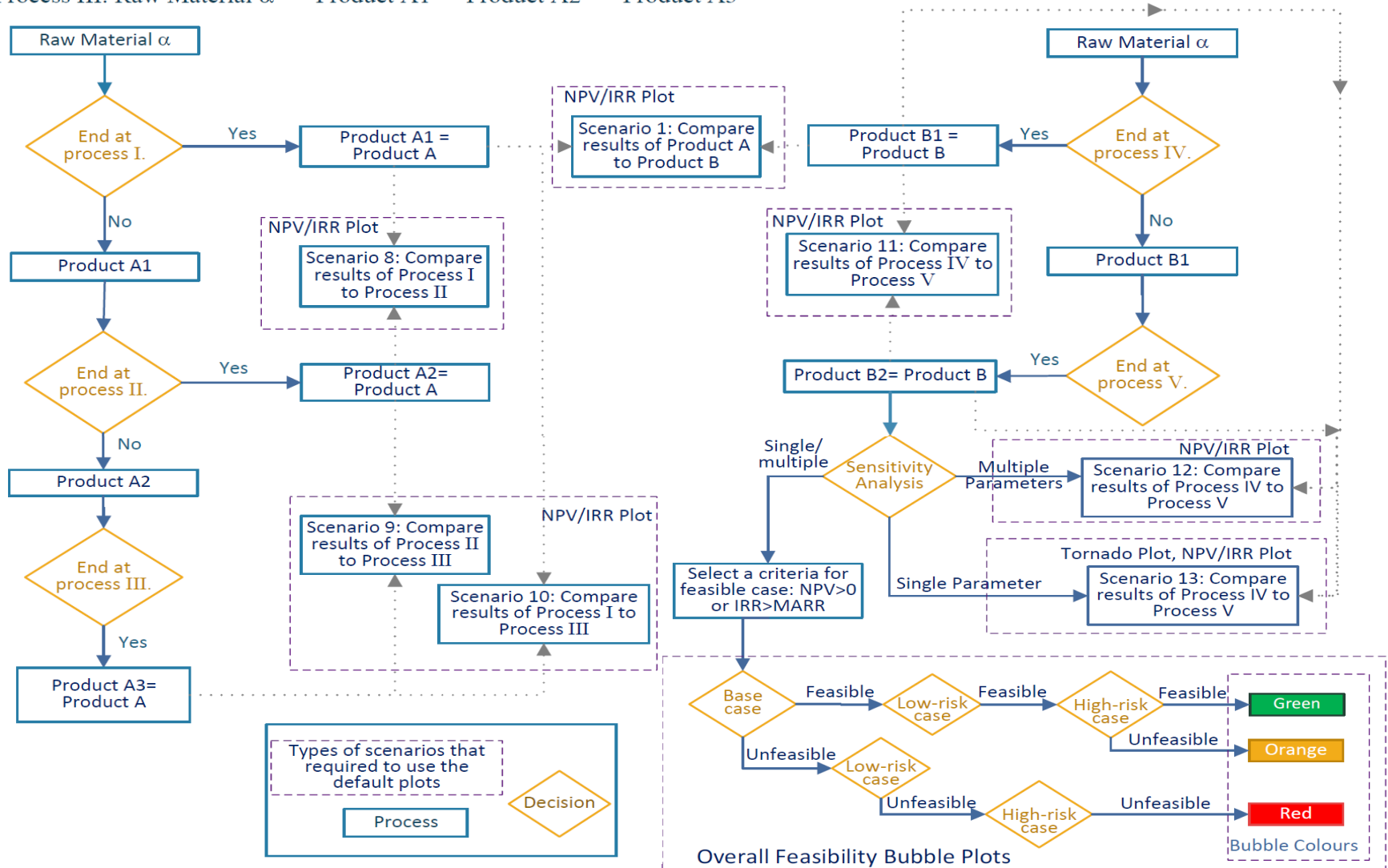


Figure 5.15: A summary of the various scenarios that can be plot in S-BEAT

5.1.9 The Minimum Selling Price Seeker sheet

The *Minimum Selling Price Seeker* sheet was added to S-BEAT subsequent to the second publication (Chapter 4). In Chapter 3, the cost of the intermediate sugar mill streams (clear juice) was assumed. In Chapter 4, a material flow cost accounting approach was applied to estimate the cost of producing the intermediate mill streams. A boundary was drawn around each section of a generic sugar mill MATLAB model so that the intermediate mill streams of interest exited the boundary. The capital expenditure and total production costs were calculated per section with the mass and energy balance from the generic mill model, and the value of the intermediate mill streams was estimated.

Whilst this approach generates a useful output, a basis did not exist by which the costs could be verified. Furthermore, each sugar mill in operation in South Africa is unique, their configurations, capacities, energy utilization, etc. differ. Therefore, the cost of their intermediate mill streams would vary. It was decided that a range for the biorefinery raw material cost would be better suited for S-BEAT rather than a single value. Additionally, the raw material cost was converted to a Rand per tonne sucrose rather than a Rand per tonne stream. This would allow multiple streams to be assessed. A sugar mill would need to decide whether they can afford to sell their intermediate stream at the cost that the biorefinery requires. The mill would also need to determine if they can sell the stream at the required price if the blending of different streams is necessary to obtain a specific quality for the downstream processing. In future, it might be possible to buy in sugar streams that are not only sucrose based, such as cellulose hydrolysate. Hence, the change over from a Rand per tonne intermediate mill stream to a Rand per tonne “valuable component” would accommodate different feed materials.

The minimum selling price is essentially obtained by setting a range for the raw material cost, entering an initial best guess for the selling price, specifying a MARR, and choosing a plant capacity. S-BEAT includes five preprogrammed calculation blocks to obtain up to five different capacity lines with their corresponding selling prices that result in a feasible IRR for the range of raw material costs. More than five annual biorefinery plant capacities can be analysed by repeating the process in a calculation block. Constraints are added to the plot by obtaining high and low market values for the year of interest. An additional constraint can be added by determining a realistic range for the raw material cost.

The algorithm makes use of the Microsoft Excel Goal Seek function. It varies the selling price for the specified raw material cost, and plant capacity until the MARR is obtained. The product could

be sold at any price above the resulting minimum selling price line. Consider that the market value of a product is based on supply and demand. The market value is basically what a customer would be willing to pay. If the resulting minimum selling price (MSP) does not fall within the region of acceptable market values, then it is likely that a customer would purchase an alternate product.

Additionally, if the MSP is too high, the demand can diminish, and the product would need to be sold at a reduced price which could have an extremely negative impact on the company. Now consider oversupply, which occurs when the demand for a product is lower than the supply and a surplus in unsaleable inventory results. In extreme cases, an oversupply of product could make the product impossible to sell.

Perfect markets do not exist in reality. Imperfect markets, on the other hand, imply that prices are not set by supply and demand, the market contains numerous different products and services, there is competition for market share, consumers do not have all the information on products and prices and there are high barriers to entry (Connor, 2007).

High barriers to entry can be explained as the technological, legal or market forces that prevent new competitors from entering a market. Extreme cases cause a monopoly where one company can dominate the market in its entirety and control the market prices. Alternatively, cartels can result when multiple companies collude and fix prices so that they all generate a profit, as seen in the lysine cartel. Additionally, these parties can charge higher prices for reduced quality products at the expense of the customer, as there are no product alternatives (Greenlaw and Taylor, 2014).

Market share is the percentage of total shares that is generated by a company in an industry. It is a key indicator of how a company is performing compared to its competitors. When there is competition for market share, dominant companies could lower prices, introduce new products and processes, and use advertising to increase the operations and improve their profitability. The effects of market share are often seen in companies which are in mature industries or cyclical industries which have low growth. Cyclical industries are sensitive to business cycles, i.e., they are affected when customers prioritise essential expenses over non-essential expenses. Cyclical industries tend to have low margins, and they are run at maximum efficiencies because of competition. Companies are willing to accept temporary losses in revenue so that they can force competitors into bankruptcy. Once the competition is removed, they gain their market share and can increase their product prices once more. This approach was seen in the lysine cartel as well. ADM was willing to take a loss to increase their market share. When their competitors market share reduced, and they began to fear ADM, ADM approached them to form a cartel.

Market saturation occurs when a product is completely distributed to the market, and there is no longer a new demand for the product. Introducing products to a saturated market requires innovation, creativity, consistency, and a way to differentiate the product from the competition.

The aforementioned market theory should be considered when analysing the results of the minimum selling price plots. Figure 5.15 depicts the pseudocode diagram for the *Minimum Selling Price Seeker* sheet. Since Chapter 3 and Chapter 4 included numerous case studies which made use of the various plotting capabilities of S-BEAT, a case study which demonstrated the power of the *Minimum Selling Price Seeker* was included next.

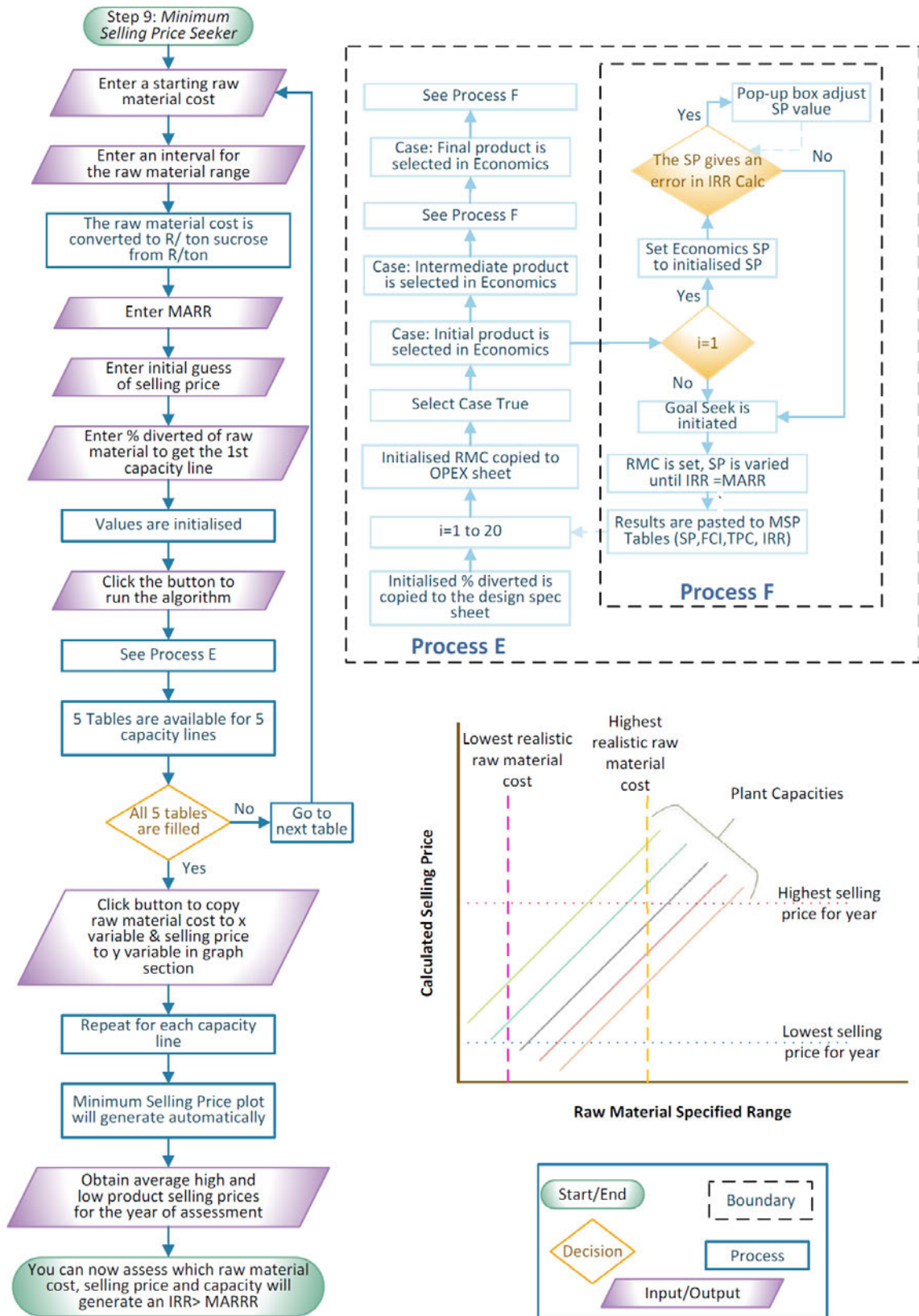


Figure 5.16: Pseudocode diagram of the Minimum Selling Price Seeker sheet in S-BEAT

5.2 Minimum Selling Price Seeker: Case studies

Two case studies were assessed to demonstrate the use of the *Minimum Selling Price Seeker*. Case studies 1 and 2 were performed on Succinic Acid (SA) and Monoethylene Glycol (MEG), respectively. The results of the overall feasibility chart in Chapter 4 showed orange bubbles for both the MEG and SA cases. The orange bubbles occurred when the Net Present Value of the *High-risk* cases was negative, whilst the *Base* and *Low-risk* cases had positive NPVs. Furthermore, the tornado plots showed that for both SA and MEG, it was the selling prices that caused the highest deviation to the NPV.

The following questions arose:

- Which product selling prices when adjusted within a reasonable range would cause the High-risk case to become feasible and under what capacity and raw material range?
- Do the resulting selling prices fall within acceptable market conditions? Does the product selling price fall within the boundary of acceptable market prices?
- Will the production capacity that is required result in an oversupply of the product?
- Is the required raw material cost reasonable and will a sugar mill sell their stream for that price?

5.2.1 Case study: Literature specifications

The inputs for each case were presented in Chapter 4, and they are replicated in Table 5.1 for completeness.

Table 5.1: Input data for the minimum selling price case studies

Product	Succinic Acid ^a	MEG ^d
Literature source	“Production of Bio-based Succinic Acid”	Intratec Solutions – “Ethylene Glycol
Raw material source	Cane Juice - assumed clear juice	Ethylene
Product capacity	77 000 t/a	750 000 t/a
Total capital investment	\$ 260 000 000	\$ 630 000 000
Reference location	US Gulf Coast	US Gulf Coast
Reference year	2014	2015
Stoichiometric equation	$7C_6H_{12}O_6 + 6CO_2 \rightarrow 12C_4H_6O_4 + 6H_2O$	$C_2H_4 + 0.5O_2 \rightarrow C_2H_4O$ $C_2H_4O + CO_2 \rightarrow C_3H_4O_3$ $C_3H_4O_3 + H_2O \rightarrow C_2H_6O_2 + CO_2$
Product yield	94 % ^b (assumed)	$C_2H_4O = 88 \%$
Separation recoveries	95 % ^c	99 % (assumed)

^a(Jenkins, 2014), ^b(Chan *et al.*, 2011), ^c(Nghiem *et al.*, 2017), ^d(Jenkins, 2015)

5.2.2 Case study: Design basis

The design basis was not changed from that specified in Chapter 4. The only difference was that the raw material streams that were used were in the form of Rands per tonne sucrose rather than Rands per tonne stream. The high and low market prices that were used for the succinic acid case were the 2018 Asian prices of R 30 500 /t and R 25 200 /t, respectively (De Guzman, 2018). The 2018 West Europe market price of R 16 000 /t and the 2018 US market price of R 12 000 /t was used for the MEG case (De Guzman, 2018).

The global biobased capacity of MEG was reported to be 175 kt/a from producers India Glycols Ltd, HaldorTopsoe, UPM, Avantium and ENI/Versalis (de Jong *et al.*, 2020), whilst the global biobased capacity of succinic acid was reported to be 34 kt/a from producers Myriant, Succinity (BASF/Corbion), and Reverdia (Roquette) (de Jong *et al.*, 2020). It bears noting that according to a news report by McCoy (2019), the BioAmber 30 kt/a succinic acid plant in Sarnia, Ontario closed and filed for bankruptcy in 2018. The 14 kt/a succinic acid plant that was built by Myriant in Lake Providence, Louisiana was idle from 2018 as the bio-succinic acid could not compete with lowered petrochemical prices which resulted when shale oil and gas flooded the market. The 10 kt/a Reverdia succinic acid plant in Cassano Italy, however, remained operational (McCoy, 2019).

5.2.3 Case study: Results and discussion

Figure 5.17 shows the minimum selling price plot for succinic acid. Plant capacities ranging from 5 kt/a to 103 kt/a were shown. The raw material cost ranged from 0 – 6000 R/t sucrose and the succinic acid selling price ranged from 10 000 – 40 000 R/t succinic acid. The selling price was constrained between the maximum and minimum 2018 Asian prices of R 30 500 /t and R 25 200 /t. Figure 18 can be explained with the following scenarios:

Scenario A: If a plant capacity of 10 kt/a was to be selected, and if the raw material stream could be purchased from a sugar mill for R 4000 / t sucrose, then the plant will have an IRR that is higher than 20 % if the succinic acid is sold at any price higher than R 27 000 /t. This scenario would be reasonable as point A falls within the market price constraints.

Scenario B: If the highest succinic acid market price constraint were to shift towards the minimum bound, then the plant would only be feasible if the raw material cost were R 2 200 / t sucrose or less.

Scenario C: If a plant capacity of 20 kt/a of succinic acid were to be selected, with a raw material stream cost of R 4 000 / t sucrose, then an IRR greater than 20 % would be achievable for a broader range of the selling prices. The product could be sold anywhere upward of R 22 200 /t. Considering the Asian market price fluctuated between R 25 200 and R 30 500 in 2018, point C would have more flexibility and would hence be a lower-risk scenario than A.

If demand does not exist for succinic acid and the global production capacity remains at 34 kt/a, then it would be unlikely that a higher capacity plant would be built. The 103 kt/a capacity lines were represented for clarity of the case study that was presented in Chapter 4. The succinic acid plant became unfeasible under the high-risk case. This case was represented by a 20 % increase in the raw material cost and FCI and a 10 % decrease in the selling price. The tornado plot demonstrated that deviations to the NPV occurred in the order of selling price > FCI > raw material cost.

Scenarios D and E: The solid 103 kt/a line and corresponding point labelled D represents the base case scenario (as per Chapter 4) with a selling price of R 16 325 /t and raw material cost of R 368 /t clear juice which corresponded to R 3 200 /t sucrose. The dashed 103 kt/a capacity line shifted because of the 20 % increase in the FCI. The point labelled E corresponds to the 10 % decrease in the selling price and the 20 % increase to the raw material cost. Label D was originally above the minimum selling price line and hence had a positive NPV and an IRR greater than the MARR. Point E, however, fell under its corresponding line (orange dashed line) which is why it became unfeasible. For it to have remained feasible, the selling price would have needed to be above the MSP of R 16 200 /t.

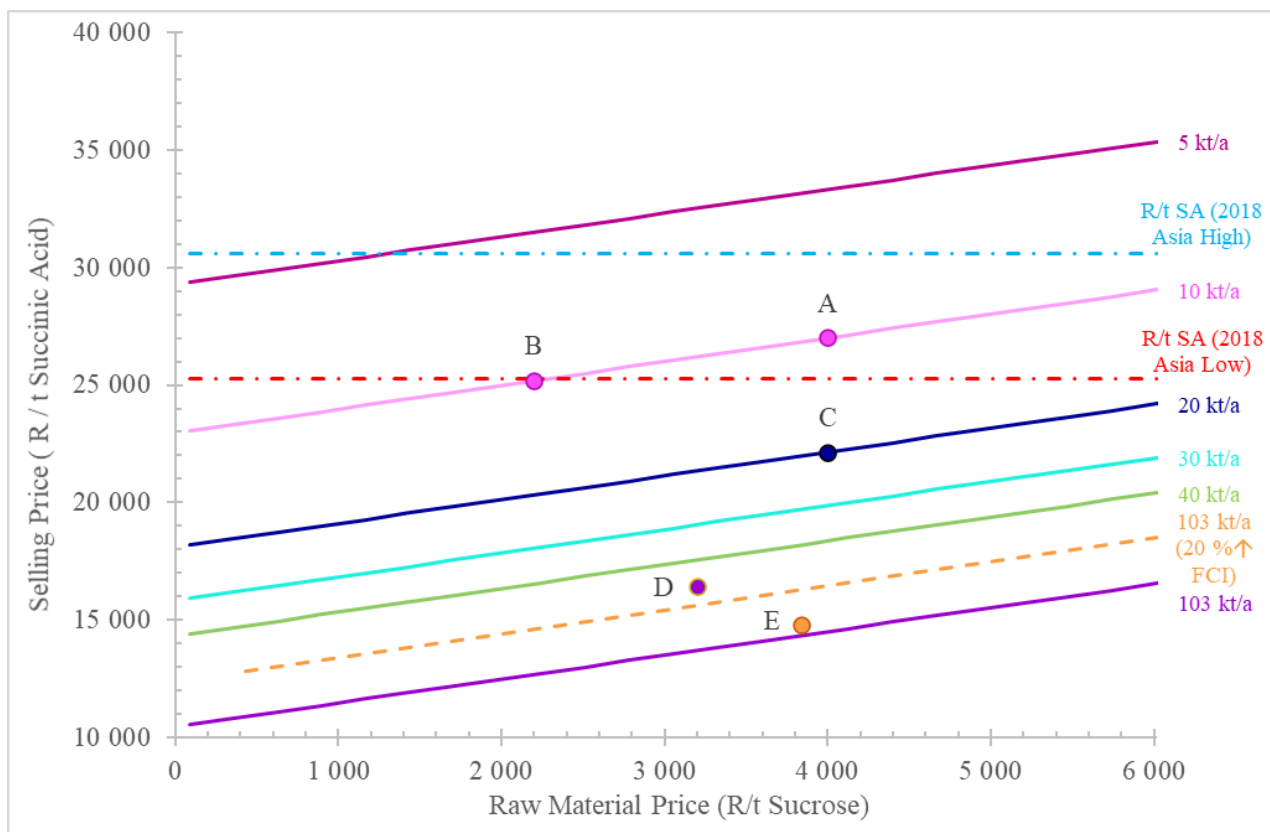


Figure 5.17: Succinic Acid Minimum Selling Price plot for different plant capacities

Figure 5.18 shows the results of the MEG plant. Plant capacities ranging from 30 kt/a to 175 kt/a were shown. The raw material cost value ranged from 0 – 6000 R/t sucrose, and the MEG selling price ranged from 10 000 – 25 000 R/t MEG. The selling price was constrained to the maximum 2018 West Europe market price of R 16 000 /t MEG and the minimum 2018 US market price of R 12 000 /t MEG. The global production capacity of MEG was 175 kt/a. Consider the following scenarios depicted by the points in Figure 5.18:

Scenario F: For a plant capacity of 100 kt/a MEG, with a raw material cost of R 4000 /t sucrose, a minimum selling price of R 18 000 /t MEG would be required for the plant to have an IRR of 20%. Since this minimum selling price was outside the market price constraints, scenario F would be unlikely.

Scenario G: For a plant capacity of 100 kt/a MEG, with a raw material cost of R 2000 /t sucrose, a product minimum selling price of R 14 000 /t MEG would be required for the plant to have an IRR of 20 %. The minimum selling price of this scenario falls within the market price constraints. If the market price fluctuated between R 14 000 /t and R 16 000 /t, then the plant production would be feasible. However, it would be risky if the product price tended towards the lower bound of the market price. Additionally, the raw material cost price was relatively low. It might be

problematic to reach an agreement with a sugar mill to sell their stream at that low cost. This scenario would also be unlikely.

Scenario H: For a plant capacity of 175 kt/a, which is the current global production capacity of MEG, and a raw material cost of R 3000 /t sucrose, the plant would require a minimum selling price of R 14 700 to obtain an IRR of 20 %. Whilst this scenario has a higher raw material cost than scenario G, the minimum selling price is closer to the higher bound of the market price constraint. It would be less flexible to fluctuations in the market price. This scenario is probably unlikely as well. Additionally, it would be unwise to oversupply the market.

Scenarios I and J were included in response to the overall feasibility plot, and the tornado plot results in Chapter 4. The solid orange line depicts the base case scenario whilst the dashed blue line represents an increase of 20 % to the FCI. It is clear why an instance of the base case scenario, i.e., the scenario I was feasible for the 50.76 kt/a plant, the selling price used was much higher than the required minimum selling price. Similarly, it is clear why scenario J resulted in an unfeasible situation for the MEG plant, as the selling price used was much lower than the required minimum selling price. Both scenarios I and J would not be able to compete with the 2018 market prices. These scenarios are, therefore, unlikely to occur.

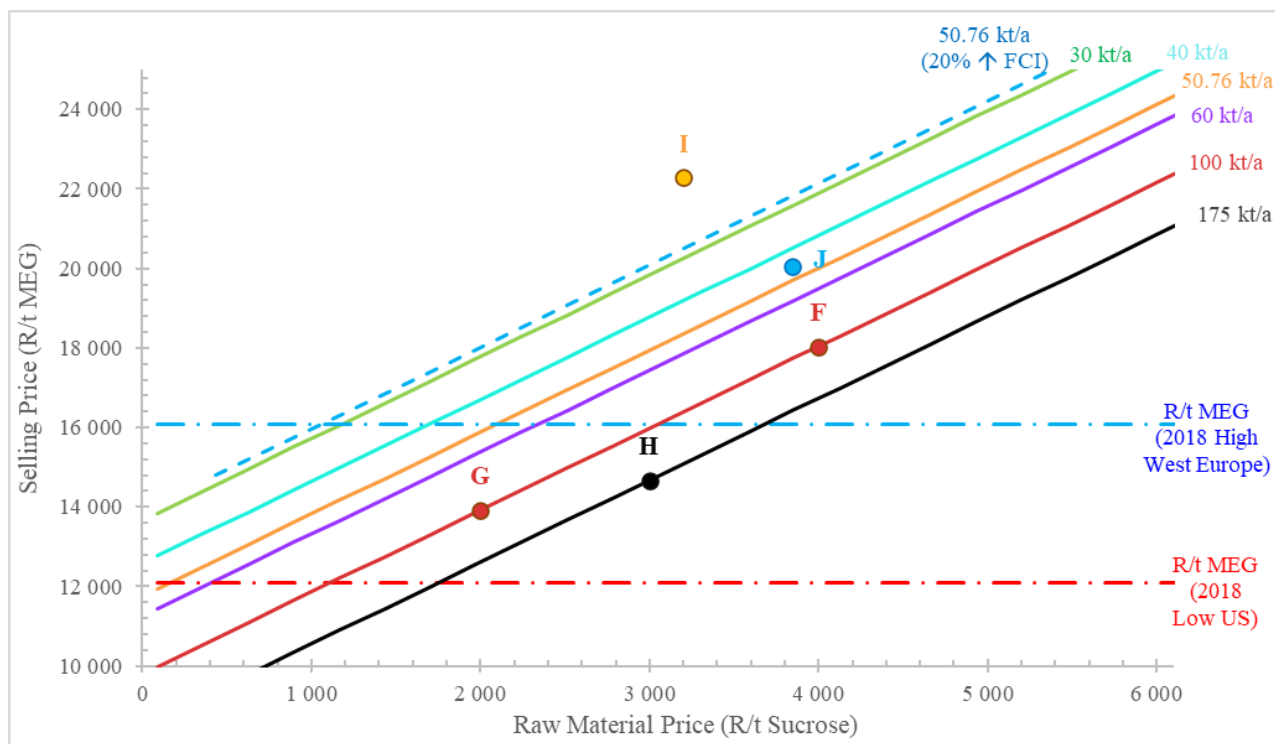


Figure 5.18: MEG Minimum Selling Price plot for different plant capacities

The differences between succinic acid and MEG case studies are apparent. The glaring difference is that the succinic acid plot can accept a broader range of raw material costs, whilst remaining within the market price constraint. Whilst the market price for succinic acid is much higher than that of MEG, many succinic acid capacity lines fall under the lower market price bound. They would inherently provide more flexibility in selecting a selling price. The global production capacity of succinic acid, however, was low at 34 kt/a, and it is unlikely that the higher plant capacities would be installed especially since many succinic acid plants were idle in the 2019 year. Unless there is a massive uptake in BDO that is made from succinic acid, it is unlikely that a higher plant capacity would be needed. A standalone succinic acid plant would likely be unfeasible.

The MEG, on the other hand, has a much higher global production capacity, as such a range of lower plant capacities could be installed without flooding the market. The problem, however, lies with the acceptable raw material costs being too low for these lower plant capacities, as well as the market price constraint. The MEG scenarios are inherently inflexible with regards to selecting the selling price as well as a reasonable raw material cost. If the MEG plant cannot get a supplier of a raw material stream at the required low costs, then they would need to sell the MEG at higher than market value prices. If other MEG producing facilities reduce the market value of MEG, then the new plant would not be able to compete, and the plant would likely go out of business.

Both case studies indicate that the relation between feedstock costs, selling price and market size are not ideal. It is, therefore, more than likely that succinic acid and MEG would not be the first products that are promoted to a more detailed cost estimation phase.

5.2.4 Special case study: Lysine HCl

A different approach was taken for the analysis of lysine HCl to that of succinic acid and MEG. This was due to the SA Bioproducts lysine HCl facility being operational in Umbogintwini, Durban, South Africa from 1995 until 2011. SA Bioproducts terminated production of lysine HCl in 2011 because they could not renew the supply contract that they had with SASA. The new pricing structure would have caused SA Bioproducts to produce the lysine HCl at a loss (ITAC, 2011).

The lysine facility that was operational in South Africa used a high test molasses (HTM) stream as their feedstock. According to Rein (2007), high test molasses is produced as an alternative to sugar, rather than as a by-product. According to Ahmed et al. (2001), the HTM that was supplied by the Tongaat-Hulett Refinery was produced by blending the refinery jet 4 liquor with the raw house molasses. The HTM that was supplied to the lysine facility was a partially inverted product. The HTM was diluted to 55° Brix and inverted with yeast. The HTM was then concentrated to 78° Brix and sent to the lysine facility (Ahmed, 2001). In 2000, the selling price of high test molasses was R 850 per ton, whilst the final molasses was R 164 (Bernhardt *et al.*, 1999). The prices of high test molasses were not disclosed in literature for more recent years.

Prior to the termination of the production of lysine HCl, SA Bioproducts experienced difficulties with low priced imports of lysine HCl, that caused them to lose market share. As they were the only producers of Lysine HCl in South Africa, they filed numerous reports with ITAC to provide safeguards on the import of lysine from all countries except for developing countries (ITAC, 2007).

Where this assessment differs to that of SA and MEG, is that a feedstock constraint was required in addition to the lysine HCl market price as it was the feedstock cost that ultimately caused SA Bioproducts to terminate the production of lysine HCl.

According to Jensen and Balkissoon (2015), the refinery jet 4 can be exhausted in a recovery house to recover sugar, or if the raw sugar factory has a back-end refinery, then the jet can be recycled to the raw syrup tank. It was considered that a mill might prefer to recover sucrose from the refinery jet rather than inverting the stream and producing HTM. If this were to happen, the

lysine facility would need to purchase the HTM for a higher price than what the mill would sell the recovered sucrose for, i.e., the sugar. Considering that domestic prices of sugar are not readily disclosed, the US Sugar No. 11 Futures price was used to set the feedstock boundary (Investing.com, 2020).

Two assessments became possible for the lysine case, firstly, the results of the 2018 plant in Chapter 4 could be assessed. Additionally, the market price and feedstock cost for the year 2011 could be applied to the capacity of the SA Bioproduct plant to determine whether S-BEAT would predict that the plant would be unfeasible under those conditions.

The literature data and cases studies that were presented in Chapter 4 were used for this assessment. To summarise:

- A lysine plant with a throughput of 67 851 t/a that used a sugar mill syrup stream as the feedstock was presented. The product selling price was R 26 000/t, and the feedstock cost was equivalent to R 3 554/t sucrose. The resulting NPV of the plant was R 1 831 million after 25 years for a MARR of 20%. The IRR of the plant was 27.86%.
- A lysine plant with a throughput of 19 202 t/a that used a sugar mill A-molasses stream as the feedstock was presented. The product selling price was R 26 000/t, and the feedstock cost was equivalent to R 3 763/t sucrose. The NPV of this plant was R –32 million after 25 years for a MARR of 20%. The IRR was 18.56 %.
- A lysine plant was modelled receiving A-molasses from two mills hence having double the throughput and produced 38 404 t/a of lysine HCl. The product selling price was R 26 000/t, and the feedstock cost was equivalent to R 3 763/t sucrose. The NPV of this plant was R 487 million after 25 years for a MARR of 20%. The IRR was 23.17%.

The SA Bioproduct facility originally had a plant capacity of 10 800 t/a. However, towards 2011, the plant could produce between 16 000 -18 000 t/a (SA Bioproducts, 2013). For this case study, additional capacities of 10 800 t/a and 17 000 t/a were investigated as well as a larger 100 000 t/a capacity plant. The data for the market price constraints were obtained for the high and low Chinese locally transacted prices for the years 2011 (eFeedLink, 2011) and 2018 (eFeedLink, 2018).

Figure 5.19 provides the results of the MSP plot for the assessment of the 2018 sugar feedstock costs and lysine market prices, whilst Figure 5.20 presents the same assessment but with the boundaries adjusted for the 2011 high and low sugar and lysine market prices. With regards to

both Figure 5.19 and Figure 5.20, for a capacity to be feasible, two conditions would need to be met:

- The capacity line would need to fall within the market price constraints, or it would need to lie below the minimum boundary for the plant to be feasible for a range of acceptable market prices
- For the best-case scenario, regarding the feedstock cost, the capacity line would need to lie to the right of the “sugar 2011/2018 low” constraint. For the worst-case scenario, the capacity line would need to lie to the right of the “sugar 2011/2018 high” constraint.

In Figure 5.19, Scenario K corresponds to the molasses feedstock, whilst scenario M corresponds to the syrup feedstock. The following conclusions can be made:

- Whilst Scenario M does lie above the MSP line, and hence would provide a positive NPV and an IRR that is higher than the minimum of 20%, the market price that was selected was too high. Scenario M does lie to the left of the best-case scenario of the sugar price. However, it was a requirement that both conditions are met.
- Scenario K can be used for both the 19.2 kt/a line and the 38.4 kt/a line as this corresponds to the lysine plant which receives molasses from one mill and two mills, respectively.
 - Scenario K falls under the 19.2 kt/a line, so the IRR of the plant would be lower than the minimum. Scenario K would be immediately rejected.
 - Scenario K does fall above the 38.4 kt/a line. However, the argument of scenario M holds, and scenario K would be rejected as well.
- As per the plot, the 67.85 kt/a plant capacity and the 100 kt/a plant capacity fall within the feasible area. The 100 kt/a plant capacity has more flexibility than the 67.85 kt/a plant. This means that a selling price can be selected in the range of R 17 000/t - R 20 000/t for the plant to be feasible. The plant could also afford to pay between R 3 100/t sucrose and R 5 000/t sucrose.

In this instance, the higher plant capacity resulted in less risk when compared to the lower plant capacities.

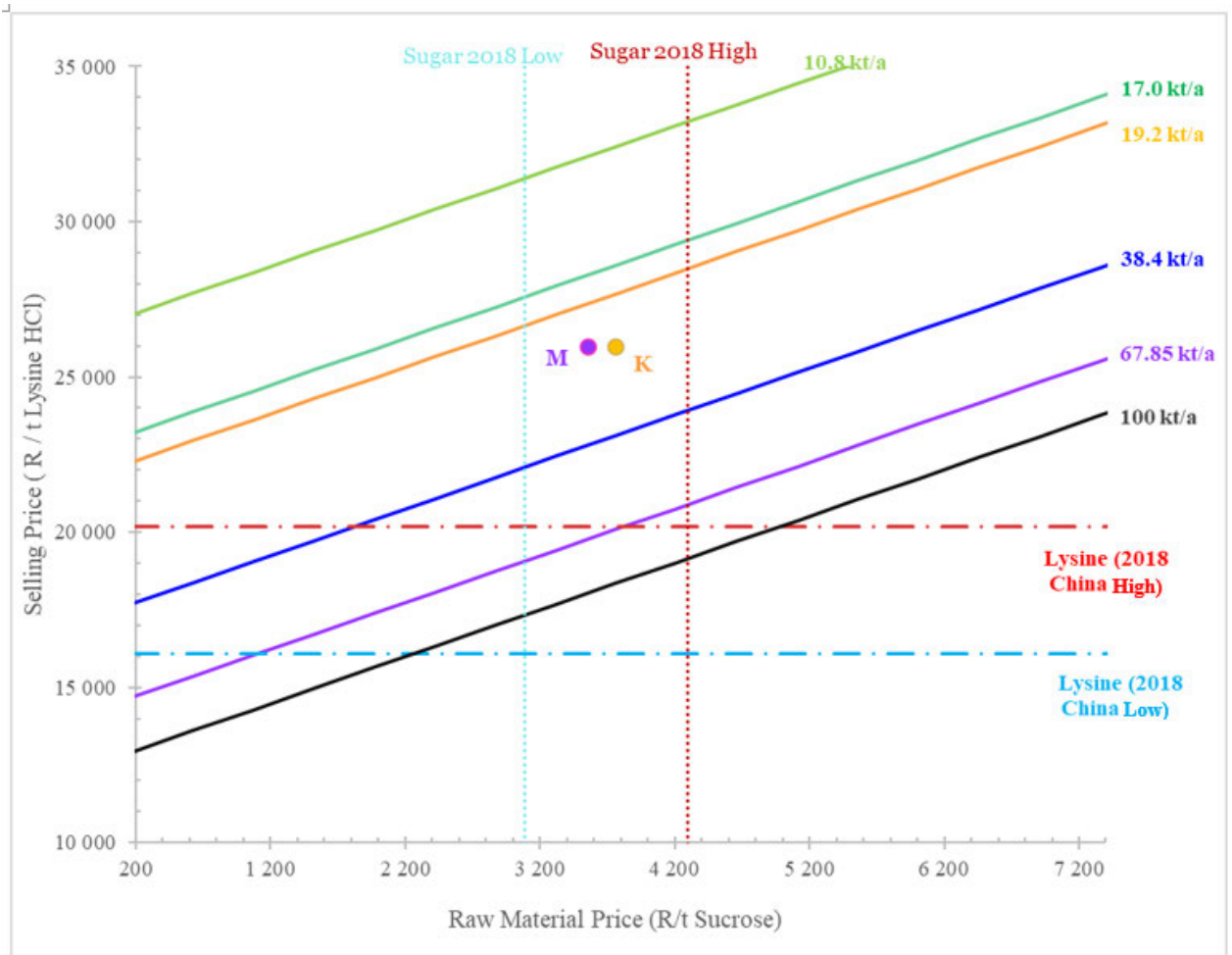


Figure 5.19: MSP of Lysine for the 2018 scenario assessment

Figure 5.20 was used to determine whether S-BEAT would predict that a plant which had a plant capacity of either 10.8 kt/a, or 17 kt/a would be able to purchase the feedstock at prices that were equivalent to or more than the sugar price in 2011 and remain feasible. It can be seen that regardless of the feedstock cost, S-BEAT predicts that the minimum selling price required for a plant of low capacities (Scenario N and O) would not fall within the acceptable market price range for lysine HCl. In other words, this plant would be unfeasible based on the required selling price. This assessment was done on plant data that was escalated to the year 2018. Hence it is not directly comparable to the lysine facility that closed in 2011. However, the result still holds that for a low-capacity plant, the minimum selling price would be considerably higher than that of a higher plant capacity. Scenarios' Q and P depicts this reasoning:

- Scenario Q is feasible as the plant would be capable of selling their product for a wide range of prices, which falls within the market price boundary. Additionally, the plant would be able to purchase the feedstock for higher than not only the best-case sugar price of 2011 but also for higher than the worst-case scenario for the sugar price of 2011.

- Scenario P depicts that there is only a slight margin above the worst-case scenario for the sugar price, for which the plant would be able to sell their product at the market price range while remaining feasible.

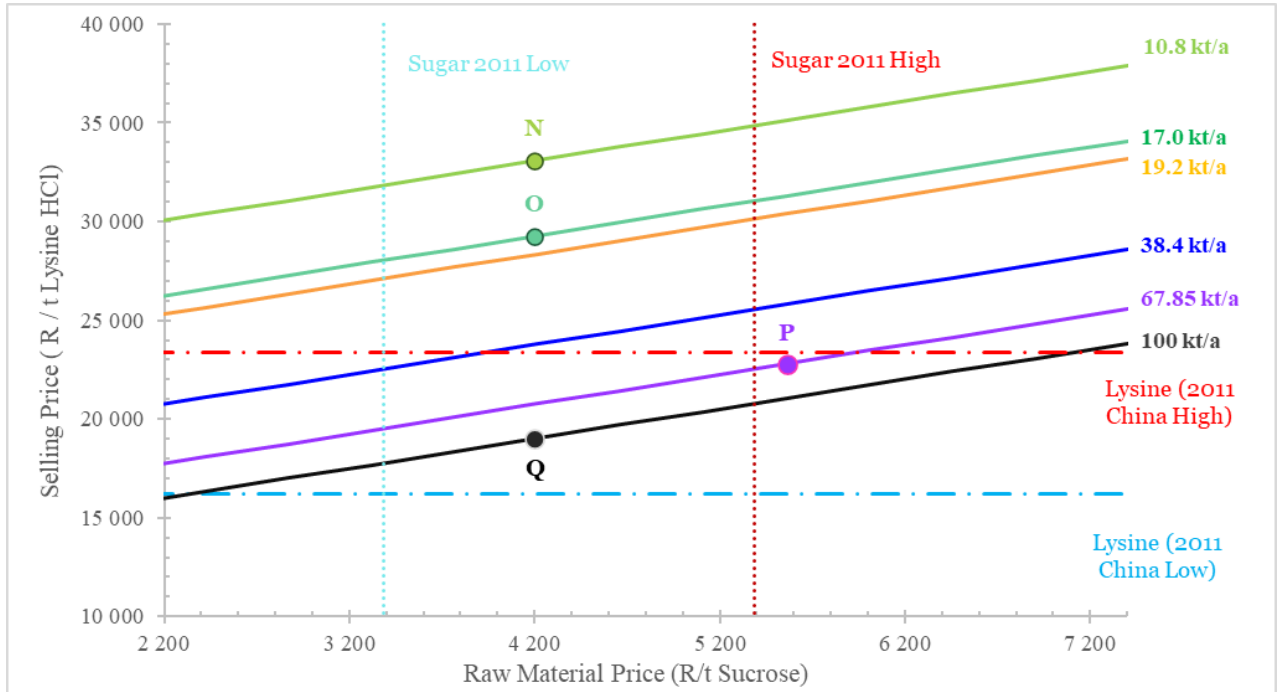


Figure 5. 20: MSP of lysine showing the 2011 scenario assessment

The intention was to show that the feedstock cost would have a greater effect on the feasibility of the lysine facility. However, it was clear that for a plant constructed in 2018, the market price and plant capacity had a more significant impact on the overall feasibility.

The lysine case study illustrated the importance of the production volume relative to the world market size, the number of players in the market and the sensitivity of a project's feasibility to variations in the feedstock and product market prices. Safeguards should be put in place if only a few market players control the market of a particular product. The biorefinery should be prepared for the worst-case scenario, which would be difficulty in gaining market share, reduced market prices and extreme dumping of imports on the domestic market. Additionally, it would be important to secure a contract with the suppliers of the feedstock, paying considerable attention to the rate of inflation that the feedstock cost may experience. A project's feasibility will be inherently uncertain under conditions that cannot be controlled, such as the behaviour of market players, market sizes, market prices and feedstock costs. It is important to recognise these uncertainties and to use these parameters in sensitivity and scenario analysis so that a complete picture can be presented.

5.3 Discussion of features in S-BEAT

One of the most notable features of S-BEAT is its ability to allow a user to make quick adjustments to values, so that they may apply company-specific information instead of using the default values. In this sense, the default values are more suited for demonstration purposes. If S-BEAT were to be employed by members of the sugar milling community, then they should use company-internal data to perform comparisons.

S-BEAT also allows for multiple products in a processing route to be assessed at the same time, which means that numerous comparisons can be generated with just a few added pieces of information as seen in Chapter 5. It is known that the order of magnitude method is only used in the earliest phases of a project design because of the discrepancies which exist with limited information. In this regard, S-BEAT included a comprehensive way to analyse uncertainties related to process information, model information and external information like raw material and product market price fluctuations. The results of these assessments can be expressed by tornado plots and overall feasibility charts and other automated graphs.

In Paper 2, new estimates for the sugar mill streams were estimated by using the mass and energy balance results of the generic sugar mill MATLAB model. The sugar mill was broken down into different sections, and the cost of obtaining the product which left each section was generated. The cost of production was then used as the feedstock cost for the intermediate streams in S-BEAT. Whilst this approach worked, it was considered to be better if a range of feedstock costs were applied to the model rather than a fixed value: Each South African sugar mill is different; their configurations are different; energy consumptions are different; the age of their equipment is different. Each company, when conducting a material flow cost assessment, would generate a different cost for their intermediate mill streams. The overall aim would be to sell their streams at a price which would not negatively impact their sugar production. However, considering all the problems the sugar industry is currently facing it would be reasonable to assume that diverting a stream from the mills' operations would reduce the amount of surplus sugar that would be sold at a loss on the world market. With this in mind, the minimum selling price seeker was implemented in S-BEAT.

The question that was asked of the seeker was what combination of plant throughput and feedstock cost would produce the minimum selling price that the plant requires to obtain an IRR of 20 %. The power of the seeker is seen when constraints are added to the plot. These constraints include the global production volume of the product so that throughputs that would oversupply

the market are not investigated. Constraints can be added to the feedstock costs so that a reasonable range is evaluated. On the feedstock cost, it was decided to substitute the cost per stream, to a cost per ton sucrose, in that way a range of different streams could be assessed by one plot, rather than limiting the seeker to one mill stream at a time.

Additionally, it would allow for comparisons to be made between different products on a Rand per ton sucrose basis. It would be the mill's responsibility to determine whether they could afford to sell a stream at the required price per ton sucrose. Additionally, if the plant was to be designed for a certain quality of the feedstock, then the sugar mill can blend different intermediate streams until the correct stream concentration is met. The mill would need to decide on the appropriate price for the feedstock in this instance.

Perhaps the most significant constraint that can be added to the minimum selling price seeker plot is on the maximum and minimum market prices that were seen for the product. An ideal scenario would be one in which:

- The throughput is significantly below the global production volume;
- The feedstock cost accommodates the cost of production of a sugar mill stream;
- The cost of production that demands a product selling price to fall within the maximum and minimum market prices, or ideally below the minimum market price.

By considering these three concepts together, the flexibility of a company to react to market price changes is highlighted. Additionally, the focus can be placed on improving various aspects of the design when a more detailed design stage is employed for the product.

The minimum price seeker graphs provide insight to the uncertainties in the market price, feedstock costs and production volumes. The overall feasibility plots demonstrate which products should be passed on to the next design phase, which uses more time and resources to investigate the techno-economic of the product.

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CHAPTER 6: CONCLUSIONS, OUTLOOK, AND FUTURE WORK

6.1 Conclusions

The South African Sugar Industry requires its surplus sugar to be diverted to the production of biofuels, biochemicals or cogeneration of electricity. If this is done, then the losses that they incur from exporting sugar would be reduced. With the implementation of the “South African Sugarcane Value Chain Master Plan, to 2030”, the industry is preparing to assess the different diversification strategies that could lead to sustainability.

Whilst techno-economic assessments have been conducted in the past, their values are static, and it would be preferable to have a tool that can quickly respond to the changing economics that surrounds biofuels, biochemicals and cogeneration. The tool should also be able to incorporate the uncertainties that exist in the biorefinery space, particularly the raw material costs and the product selling prices. This study was conducted to develop such a tool.

The main research question, reflecting the aim, was: How can a preliminary cost estimation method be implemented into an easy-to-use tool, for diversification projects in the South African Sugar Industry, that can provide the CAPital EXpenditure (CAPEX), OPERational EXpenditure (OPEX), as well as an economic analysis and comparison of various bioproducts and process alternatives? A secondary aim was to design the tool such that additional products and processes could be included in future research. Furthermore, an extension to other feedstock streams should be possible.

The objectives of this work were the following:

- To design a platform which should be easy to use, guiding the user to provide the relevant input when assessing a new product, while standardising other parameters and assumptions using the same assessment routine. This was deemed essential to enable the comparison between products and processes at a similar level of certainty.
- To identify and apply capital and operational cost estimation methods to obtain a conceptual order-of-magnitude estimate of various biorefinery processes existing elsewhere, at a typical SA sugar mill capacity, taking SA specific costs into account.
- To calculate and make use of well-known economic indicators to make an informed decision on which products will be economically beneficial to the sugar industry.
- To incorporate a routine for economic analysis and comparison of different biorefinery products, including a sensitivity analysis.

- To conduct a techno-economic assessment for several potential biorefinery products to demonstrate the capabilities of the toolbox.
- To quantify the uncertainties that are present in the results of S-BEAT due to the preliminary estimation method, the uncertainty in biomass and bio-product price. To use the uncertainty when analysing which products are feasible or not.

Each objective was met during the development of S-BEAT. A preliminary cost estimation method was applied to design an easy-to-use tool, which allows for the comparison of different biorefinery products and process alternatives on a consistent basis. S-BEAT was developed to be a comparative tool, and the various scenarios that have been assessed have demonstrated this purpose. S-BEAT can compare different biorefinery products that originate from the same feedstock, a comparison can be made for the same product which originates from different feedstocks, and different feedstock capacities for the same product from the same mill stream can be assessed. S-BEAT has the potential to compare the economic feasibility based on data from different literature sources and technologies for the same product. In future, S-BEAT should evaluate the cost of a single product from multiple existing technologies, if the capital cost is available for the technologies.

S-BEAT was developed on the easy-to-use Microsoft Excel platform, the methods which are present in S-BEAT uses the same assessment routine, similar and traceable assumptions and the same level of certainty when evaluating the economics of different products. Capital and operational estimation methods were implemented, which resulted in a conceptual order-of-magnitude estimate of various biorefinery processes which exist elsewhere, in the South African context. In future, the factorial estimating method can be implemented by using the equipment costs that are published in literature designs. The results of the order-of-magnitude cost estimation of an existing plant can then be compared to the factorial estimate of the same plant whose costs are sourced from literature.

The Net Present Value (NPV), Internal Rate of Return (IRR) and discounted Payback Period (PBP) were selected as the economic indicators within S-BEAT, and the economic feasibility of several products was identified. It was assumed that these indicators would provide enough information to make informed decisions. The uncertainties that are present in S-BEAT were assessed through a deterministic sensitivity analysis, and a more statistically rigorous approach should be implemented in future.

Ethanol, ethylene, high-density polyethylene (HDPE), monoethylene glycol (MEG), lactic acid, polylactic acid (PLA), succinic acid, 1,4-butanediol (BDO), L-lysine hydrochloride and 2,5-furandicarboxylic acid (FDCA) were assessed in S-BEAT for various scenarios. It was found that ethanol, lactic acid, PLA, BDO and lysine (from the syrup as the feedstock) were feasible for most of the scenarios that were tested. Ethylene and HDPE were unfeasible irrespective of the scenario. The feasibility of succinic acid, FDCA, and lysine (from molasses as the feedstock) was influenced by the assumptions that were used.

Additionally, a minimum selling price seeker was included in S-BEAT so that insight can be obtained on whether the minimum selling price of a plant, when coupled with a range of feedstock costs and production throughputs would be competitive with existing market information of the product. Succinic acid, MEG and lysine were assessed with the minimum selling price seeker. The results indicated that the relation between feedstock costs, selling price and market sizes were not ideal for succinic acid and MEG. Additionally, lysine would only be feasible for large plant capacities at the required feedstock costs and market prices.

6.2 Identified limitations of the features in S-BEAT

One of the drawbacks that was noted was that an average seasonal throughput was used to assess the case studies presented in this work. This is an underestimation of capital expenditure. In future work, a factor should be added to the capital investment calculation so that a nominal plant capacity is used instead for the calculations. A further issue that was found was that the effects of a fully integrated plant could not be seen due to the lack of mass and energy balances. Instead, the impact of multiple stand-alone facilities which do not benefit from the reduced costs that are associated with integration such as lowered energy costs, reduced plant overheads, and reduced labour and administration costs were used in the method. In this way, it is not possible to obtain an accurate representation of what would happen if the plant were to divert streams to be sold as co-products and further assessments that require a mass and energy balance are simply not possible.

6.3 Outlook and future work

The following scenarios have not yet been considered in S-BEAT:

- The model does not take into account the non-sucrose fraction that will also undergo fermentation, this aspect should be considered in future.

- A time-utilisation factor can be implemented to account for the nominal plant capacity in the CAPEX estimation rather than using the current plant averaged throughput.
- The complexity of S-BEAT can be expanded on to include different techniques like using the exponent estimation method on individual process blocks. This technique would be similar to that of Tsagkari *et al.* (2020). A factorial estimating method can also be included so that the results of the different CAPEX methods can be assessed.
- A database of the literature information on different biorefinery plants, with the input data that is required for an assessment in S-BEAT, can be included in S-BEAT.
- A more rigorous statistical method can be applied to the sensitivity analysis, like the Monte Carlo simulation approach (Fisher, 2014).
- S-BEAT can be used in future as the basis to evaluate different raw materials like sugarcane bagasse or even sugar beet with minor modifications and adjustments.

Finally, with the implementation of the Sugar Master Plan, it would be a promising idea to use S-BEAT to generate different scenarios for a first pass screening assessment of the potential products that should be rigorously investigated. S-BEAT awaits application by the South African Sugar Industry, to assess its product recommendations with a more rigorous techno-economic analysis. The production of individual business cases should help the South African Sugar Industry to overcome its many challenges and succeed in its pursuit for sustainability by product diversification.

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APPENDIX A: PAPER I – INTERNATIONAL SUGAR JOURNAL PUBLICATION

S-BEAT: A preliminary cost estimation method for the sugarcane biorefinery*

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 $\pm 30\%$ to $\pm 50\%$, 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. A sensitivity analysis is also performed to quantify the inaccuracies that may be present in S-BEAT. 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

S-BEAT: Un método preliminar de estimación de costos para una biorrefinería de caña de azúcar*

Resumen En los últimos años, las principales accionistas en la industria azucarera sudafricana han evaluado el potencial de diversificar aún más su portafolio de productos. El método utilizado ha sido evaluar los diferentes flujos del proceso en la fábrica y analizar su potencial para producir productos de valor agregado. En principio, se pueden generar una multitud de nuevas fuentes de ingresos que servirán a mercados de diferentes tamaños y valores. La primera etapa para permitir la selección del producto o proceso más atractivo económicamente es mediante una herramienta denominada Incubadora de Nuevos Productos (NPG, por sus siglas en inglés) la cual reduce la gran cantidad de opciones a través de parámetros de fácil acceso tales como la estequiometría, capacidades y tamaños de mercado. Esta herramienta fue desarrollada por el SMRI NPC. En este documento se describe la segunda etapa de este desarrollo, donde se presenta la herramienta de análisis económico de la biorrefinería de caña de azúcar (S-BEAT, por sus siglas en inglés), que proporciona una estimación de costos y un análisis económico en una etapa de diseño de proceso preliminar para alternativas preseleccionadas. Para los procesos objetivo, con altos niveles de preparación tecnológica, se utiliza el enfoque de orden de magnitud, que utiliza los datos de plantas existentes. Esta herramienta acepta datos históricos y proyecta la inversión de capital al año en curso, mientras hace ajustes para diferentes capacidades de producto y ubicaciones de la planta. Se estima que este método tiene una precisión de aproximadamente $\pm 30\%$ a $\pm 50\%$, lo que se considera satisfactorio para una estimación preliminar de costos. Las estimaciones de costos luego se someten a un análisis económico para determinar la rentabilidad del producto y permitir la comparación entre las alternativas de proceso y producto. Para demostrar el potencial de S-BEAT, se investigó la producción de polietileno de alta densidad (HDPE) y ácido poliláctico (PLA) a partir de jugo clarificado. El análisis económico obtenido resalta el nivel de atractivo comercial de los productos según lo evaluado por la herramienta.

Palabras clave: jugo de caña de azúcar, estimación de costos, análisis económico, factibilidad, metodología, preliminar

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



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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 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 (Booyesen *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 $\pm 30\%$ (Sinnot, 2005) to $\pm 50\%$ (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

S-BEAT: A preliminary cost estimation method for the sugarcane biorefinery*

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 (clear 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 Guest¹. 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.

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 (Sinnott, 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.

$$FCI^* = FCI_{ref} \times \left(\frac{Capacity^n}{Capacity_{ref}^n} \right) \times \left(\frac{CEPCI}{CEPCI_{ref}} \right) \times \left(\frac{Location\ Index}{Location\ Index_{ref}} \right)$$

(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). 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, 2016a), 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, 2016a).

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:

$$(2) \quad FCI = FCI^* + 0.05FCI^*$$

$$(3) \quad WC = 0.1FCI$$

$$(4) \quad TCI = FCI + WC$$

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.

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 cane² 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 1: Procedure to calculate the total production costs for the product of interest

Item	Factor	Basis
Variable Production Costs		
Raw Materials	-	See <i>Raw Materials</i>
Miscellaneous Materials	10%	of Maintenance ^a
Utilities	15%	of TPC ^b . See <i>Utilities</i>
Waste Management	5%	of TPC
Fixed Production Costs		
Maintenance	5%	of FCI ^a
Capital Charges	10%	
Insurance	1%	
Local Tax	2%	
Operating Labour	-	See <i>Operating Labour and Salaries</i>
Salaries	-	See <i>Operating Labour and Salaries</i>
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)

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

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

^c (Chikava, 2018)

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

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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' salary³ result in the operating labour.

The salaries of a plant manager, process engineer, admin clerk and secretary⁴ 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 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, 2016b).

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.

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

^d (Deloitte Touche Tohmatsu Limited, 2016a) ^e (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.

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 recycling⁷ (LyondellBasell Industries Holdings BV, 2017). A simplified process scheme was then obtained from Daftaribesheli (2009).

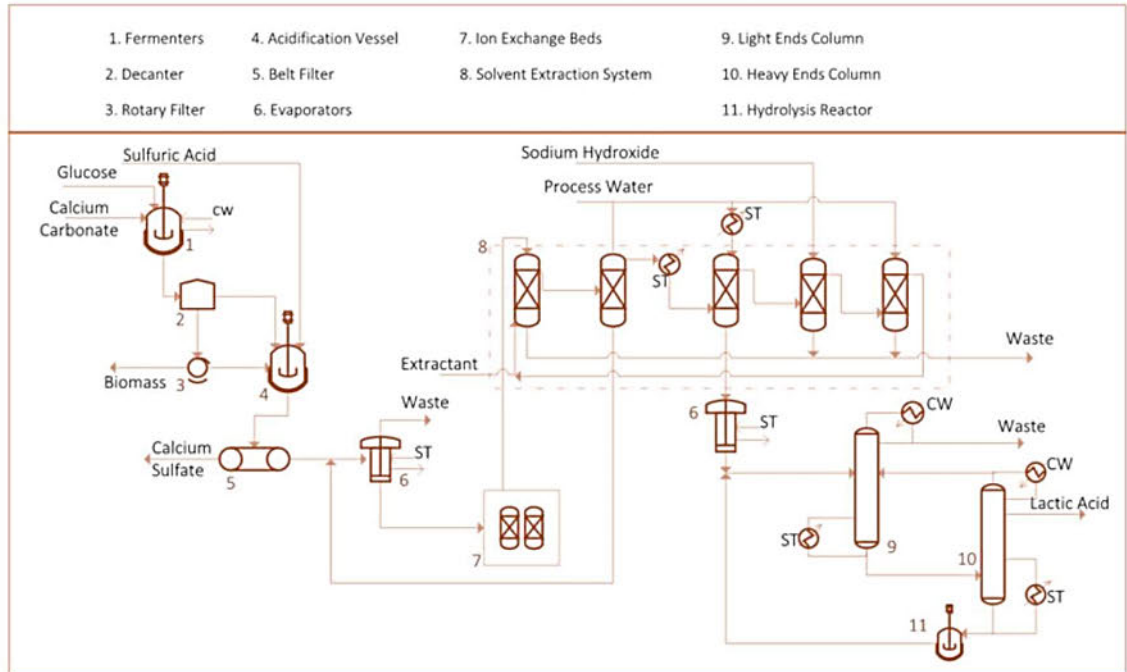
The LA reference plant information was for the Purac (now

Parameters	Ethanol ^f	Ethylene ^g	HDPE ^h	LA ⁱ	Lactide-PLA ^j
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 ^j	94.00-95.00
Overall Purity (%)	99.70 ^g	99.90	-	98.00 ^k	99.70

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

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Figure 1. Lactic acid process flow diagram adapted from Intratec Solutions (2017)



Corbion) Thailand plant. The data were obtained from various Corbion related sources. Intratec's⁸ 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 Solutions⁸ (2017), are further described below.

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 calcium lactate 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 CaSO_4 . The CaSO_4 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.

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):

Table 5: CAPEX calculation procedure and results.

Parameters	Ethanol	Ethylene	HDPE	LA	Lactide-PLA
Capacity (t/ann $\times 10^3$)	48.67	29.32	29.32	93.55	66.63
Capacity Exponent ^m	0.90	0.83	0.65	0.67	0.67
CEPCI ⁿ	576.1	576.1	521.9	525.4	556.8
Location Factor ^o	46.2	99.5	93.9	60.4	99.5
FCI (R $\times 10^6$)	300.97	262.33	479.33	1 383.87	548.13

^m (Remer and Chai, 1993), ⁿ (Chemical Engineering, 2017), ^o (Deloitte Touche Tohmatsu Limited, 2016a)

- 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.

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 633⁴ (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 ^a	Operators/unit ^a	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

^a (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 representatives⁹ 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.

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×10 ⁶)	NPV (R×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

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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.

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.

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.

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

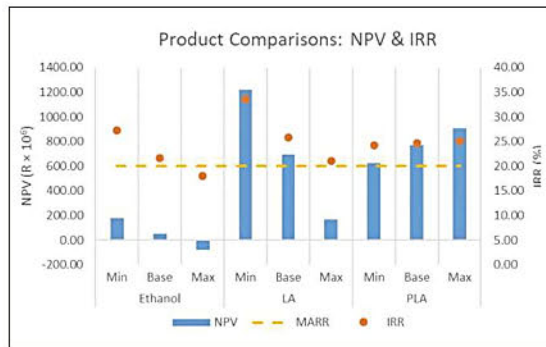


Figure 3. Net present value and payback period for the minimum, maximum and base cases for ethanol, lactic acid and polylactic acid

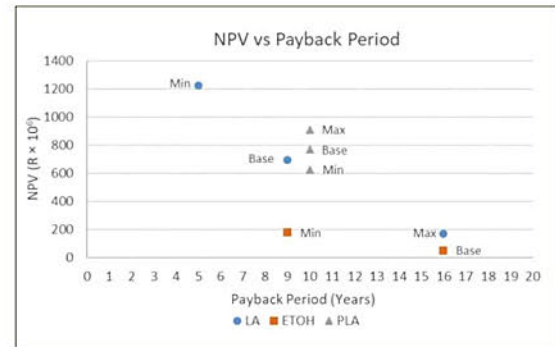
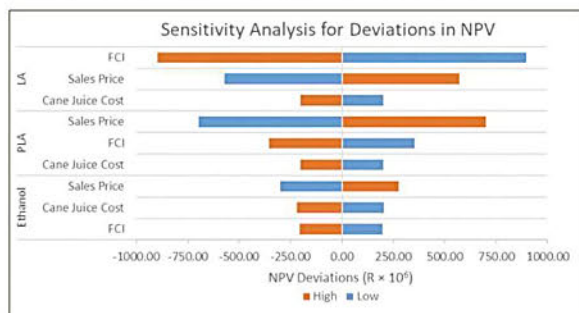


Figure 4. Tornado plot showing deviations to the baseline net present value when the fixed capital investment sales price and raw material costs are varied



The resulting plots from S-BEAT help in identifying which products perform better than others and under which conditions. Figures 2 and 3 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

S-BEAT: A preliminary cost estimation method for the sugarcane biorefinery*

- 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.

Endnotes

- 1 Personal communication, K. Guest 2017 (MSc thesis, Development and Verification of an Aspen Plus® Model of a Sugarcane Biorefinery, UKZN).
- 2 Research – SA CaneGrowers, <https://sacanegrowers.co.za/research/>, last accessed on 10 March 2018
- 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
- 5 Investing.com, <https://za.investing.com/currencies/usd-zar-historical-data>, last accessed on 11 May 2017
- 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
- 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
- 9 Personal communication, Sugar Milling Research Institute, 2016.

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APPENDIX B: S-BEAT USER MANUAL

B.1. S-BEAT structure

S-BEAT was developed as a Microsoft Excel workbook, and the Visual Basics for Applications (VBA) was utilised for the required coding. S-BEAT uses a mixture of spreadsheet coding, user forms and macro coding. Each section of S-BEAT begins on a different sheet in the workbook; these are Design Specs, Literature Specs, CAPEX, OPEX, Economics, Scenario Analysis, Sensitivity Analysis and Results. The user should preferably input data systematically in that worksheet order.

S-BEAT allows the user to investigate the profitability of a process which has up to 3 process steps. For example, the first process step could be from sugarcane to ethanol, the second step would be from ethanol to ethylene, and the last step in the process would be from ethylene to High-density Polyethylene (HDPE). Each section in S-BEAT, therefore, allows the user to input data for an initial product (ethanol), an intermediate product (ethylene) and a final product (HDPE). This functionality ensures that every product in the process route can be analysed consistently from one workbook.

B.2. *Design Specifications sheet*

1. Raw material stream specifications (See Figure B. 1)
 - 1.1. The user must select, from the drop-down, whether they wish to use the default mill model values for the raw material stream specifications or whether they wish to input their own values
 - 1.2. If the user chooses to use the default values, they must select the stream that they wish to use as the starting material for the process: Draft juice, clear juice, syrup, A-sugar, A-molasses, C-molasses and VHP (Very High Polarity) sugar
 - 1.3. A value for the percentage of the selected stream that is to be diverted from the sugar mill to the downstream processing plant must either be entered in the cell or set with the slider
 - 1.4. If different streams/compositions are to be used (in place of the default mill model values), then the user must enter the compositions for water, sucrose, non-sucrose, and crystal sugar of their stream as well as the total flow rate

Feed Source:	<input type="text" value="Sugarcane"/>		
Mill Model:	<input type="text" value="Yes"/>		
Stream:	<input type="text" value="A-Molasses"/>		
Reaction diverted:	<input type="text" value="60.00"/>		
Total Flow (tph):	<input type="text" value="17.46"/>		

	Default Values	User Values
Water	0.26	
Sucrose	0.54	
Non-Sucrose	0.21	
Crystal Sugar	0.00	
Total Flow	29.09	

Figure B. 1: The inputs required for the raw material stream specifications

- 1.5. To convert the tons per hour flow rate to a tons per annum basis; the user must either select the date for the start of the season and the end of the season or enter the operational days for the season. The user must also select the operational hours in a day (See Figure B. 2)

Total Flow (tph):	<input type="text" value="17.46"/>	
Sucrose Flowrate (tph):	<input type="text" value="9.41"/>	
Operating Period		
Cane Season: From	<input type="text" value="2019/03/20"/>	To <input type="text" value="2019/12/12"/>
Operating days:	<input type="text" value="252"/>	or Enter a value: <input type="text" value="252"/>
Operating hours:	<input type="text" value="24"/>	

Figure B. 2: The inputs required for the operational days and hours

2. Calculate the quantity of the products

- 2.1. Within each section, initial, intermediate, and final products, the user can select either 1, 2 or 3 main reactions whereby stoichiometry can be used to calculate the product quantity. (See Figure B. 3)

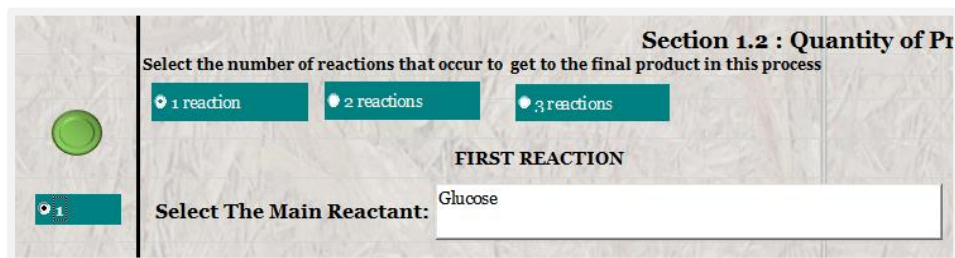
- * This functionality is important as there are often multiple reactions which occur between the initial material which enters the reactor and the final product which exits the reactor
- * An example of this exists in the production of 2,5-Furandicarboxylic acid (FDCA). Fructose undergoes an acid catalysed reaction to form 5-hydroxymethylfurfural (5-HMF) (reaction 1), the 5-HMF is reacted with methanol to yield 5-methoxymethylfurfural (MMF) (reaction 2), and lastly, the MMF is oxidised to FDCA (reaction 3)

Select the number of reactions that occur to get to the final product in this process

1 reaction
 2 reactions
 3 reactions

Figure B. 3: First select whether 1, 2 or 3 reactions exist in the processing step

- 2.2. The reactions must be entered starting with the main reactant, the order of the selection of the components in the reaction is important, i.e., the main reactant and the main product must appear in the correct blocks
- 2.3. Once the correct option button has been selected (see Figure B. 4), the green button must be pressed; this will open the user form which allows the user to select the required component



The screenshot shows a software interface with a light gray background. At the top right, the text "Section 1.2 : Quantity of Pr" is visible. Below this, the instruction "Select the number of reactions that occur to get to the final product in this process" is displayed. Three teal buttons with white text and radio icons are arranged horizontally: "1 reaction", "2 reactions", and "3 reactions". The "1 reaction" button is selected. Below these buttons, the text "FIRST REACTION" is centered. Underneath, the label "Select The Main Reactant:" is followed by a white text input field containing the word "Glucose". On the left side of the interface, there is a green circular button and a teal button with a white icon.

Figure B. 4: Instructions to input the main reactant in the first reaction

- 2.4. In the user form, the user must either select Name or Formula; they may then enter either the name of the required component or the formula that is required and select search. When the correct component is found, the component must be selected, and then the finish button must be clicked. This will populate the correct component into the correct block. Steps 2.3 to 2.4 in B.2. must be repeated for each reactant and product (See Figure B. 5).

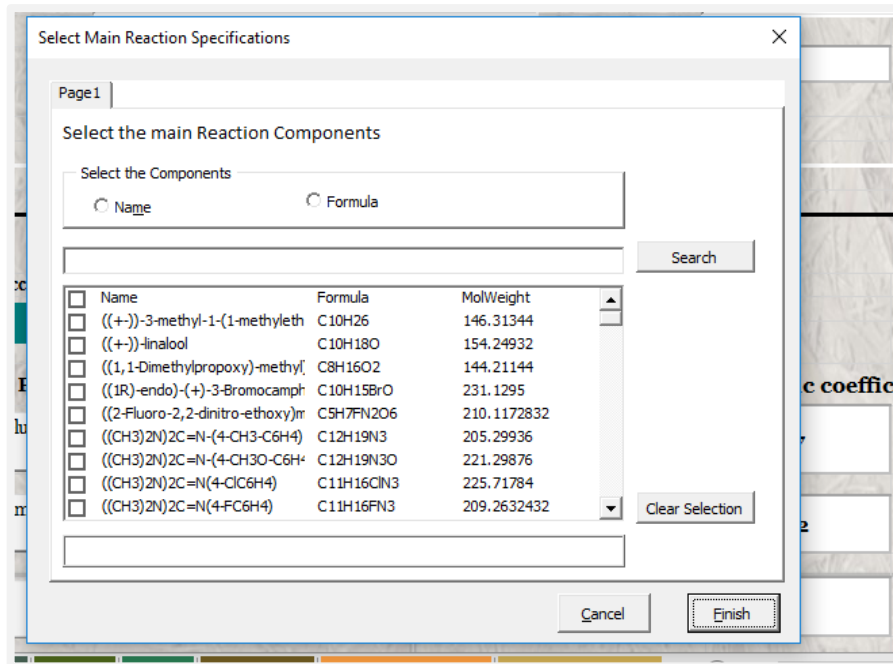


Figure B. 5: Select the required component for the reaction

- 2.5. Once the reactant and product components are populated in their respective cells, the user must enter the stoichiometric coefficients for each component (See Figure B. 6)

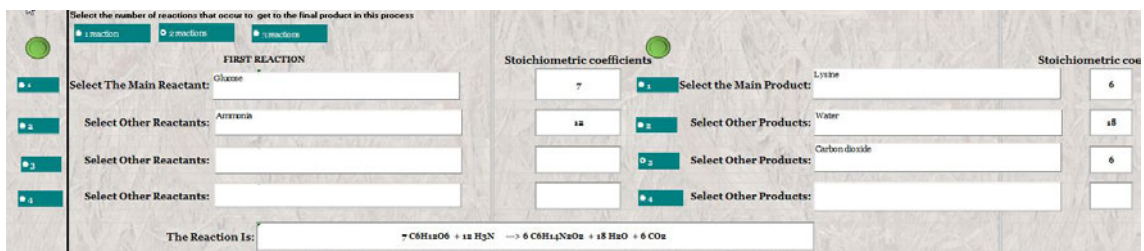


Figure B. 6: Enter the stoichiometric coefficients for each of the components

- 2.6. Next, the user must enter the reactor conversion and separation recoveries - these cannot be left blank (See Figure B. 7)

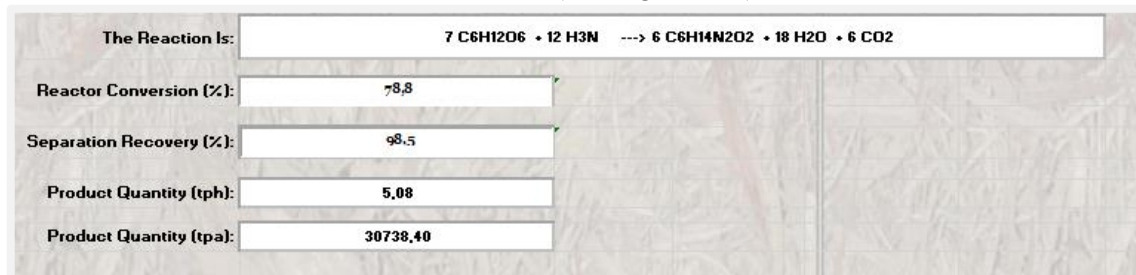


Figure B. 7: Entering the reactor conversion and separation recoveries calculates the product quantity

- 2.7. The user must repeat steps 2.1 to 2.6 in B.2. for the first, second or third reactions as well as the initial, intermediate, or final products. The product capacity is then obtained

B.3. Literature Specifications sheet

1. The user must enter the reference information for the initial, intermediate, or final products
2. The user must select which location factors to use, S-BEAT currently has two options to select from these are 2016 values from Deloitte and 2018 factors from the World Economic Forum (WEF) (See Figure B. 8)



Figure B. 8: Select which location factor to use

3. The user must select the reference location from the plant location list. The locations in the list are dependent on the location factor that was selected

With Regards to the Reference Plant:		Comments:
Data Source:	Literature Process Design	
Data Reference:	Intratec Solutions	
Plant Product:	Lysine HCL	
Designing a Similar Plant:	Yes	
Plant Year:	2016	
Plant Location:	United States	
Product Capacity:	United Kingdom	
Plant Capital Cost:	United States	
Unspecified Plant Location	Uruguay	
Plant Location	Venezuela	
Plant Location Factor	Vietnam	
Reference	Yemen	
South Africa Location Factor	Zambia	
	Zimbabwe	

Figure B. 9: Select which location the reference plant belongs too

4. The locations which are available in the WEF location factors and the Deloitte location factors differ. If the user cannot find the location of their reference plant, they must select *not specified* from the drop-down list. The option then exists for the user to specify the plant location and location factor. (See Figure B. 10)

Unspecified Plant Location	User Details	Comments
Plant Location	Thailand	
Plant Location Factor	1,4	
Reference	intratec	
South Africa Location Factor	1,2	

Figure B. 10: Input user-specified location factor values for the reference plant location as well as the new plant location. Please note that these values are dummy values which are used to show the concept

- Finally, the user must enter the reference plant product capacity and the plant capital cost to conclude the literature specification sheet. (See Figure B. 11)

Product Capacity:	100 000.00	t/a	
Plant Capital Cost:	200 000 000.00	US\$	

Figure B. 11: The user must input the product capacity and the plant capital cost of the reference plant

B.4. CAPEX sheet

- Values from the design section and the literature section will automatically be populated in the CAPEX section.
- S-BEAT has CEPCI values from 2002 to 2019. The user will need to input a CEPCI value for years later than 2019 if required. (See Figure B. 12)

CEPCI _{Ref}	541,7	Enter Latest CEPCI
CEPCI _{New}	612,7	<input type="text"/>
CEPCI _{Year}	2018	CEPCI Year
		<input type="text"/>

Figure B. 12: The user has the option to specify a CEPCI value if S-BEAT has an outdated value

- Suppose the Total Capital Investment of the reference plant was specified in step 5 of Section B.3. then the user must specify a percentage which will be allocated to the WCI, whilst the remainder of in the investment will be allocated to the Fixed Capital Investment. If a Fixed Capital Investment was specified for the reference plant, then a value of 0% must be specified for the Working Capital Investment of the reference plant (See Figure B. 13)

Section 1.1 : Total Capital Investment		
Working capital:	\$ 35 000 000,00	10,00
FCI:	\$ 315 000 000,00	

Figure B. 13: Specify the percentage of the reference plant capital investment that is allocated to the Working Capital Investment

- The user must select a capacity exponent. The user can enter a specific capacity exponent if the values that are provided are not satisfactory. (See Figure B. 14)

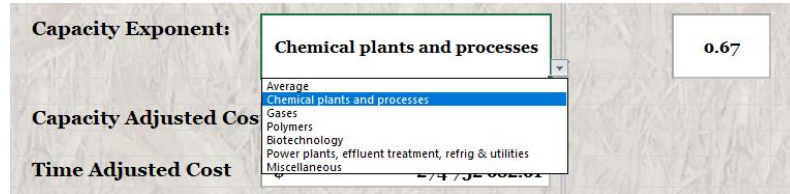


Figure B. 14: Select a capacity exponent

- A contingency factor is applied to the calculated capital investment. The user can either use the slider or input a value in the cell for the contingency factor. (See Figure B. 15)

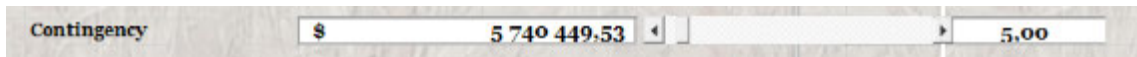


Figure B. 15: Select a value for the contingency factor

- The user can either use the slider or input a value into the cell to set the Working Capital Investment (WCI) for the new plant. (See Figure B. 16)

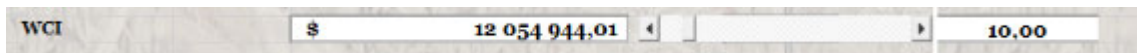


Figure B. 16: Select a value for the WCI of the new plant

- Currency conversion is done to the Working Capital Investment, Fixed Capital Investment and Total Capital Investment of the new plant. If the average exchange rate that is provided by S-BEAT is outdated, the user can go to the *Lists* tab and extend the exchange rates table. (See Figure B. 17)

Fusion Media Limited, 2007-2017. Investing.com. [Online] Available at: <https://za.investing.com/currencies/usd-zar-historical-data> [Accessed 4 August 2019].

Months	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Jan	10.21	7.62	7.19	7.82	8.96	11.12	11.65	15.89	13.48	11.87	13.26
Feb	10.11	7.72	6.96	7.50	9.03	10.76	11.67	15.87	13.13	11.80	14.09
Mar	9.56	7.29	6.77	7.67	9.24	10.53	12.13	14.77	13.42	11.84	14.50
Apr	8.46	7.39	6.57	7.77	8.97	10.52	11.91	14.23	13.37	12.47	14.30
May	7.94	7.67	6.81	8.51	10.09	10.57	12.16	15.71	13.11	12.70	14.59
Jun	7.73	7.67	6.77	8.17	9.88	10.64	12.17	14.71	13.06	13.73	14.08
Jul	7.76	7.30	6.69	8.26	9.87	10.71	12.67	13.88	13.18	13.28	14.35
Aug	7.78	7.38	7.00	8.40	10.28	10.66	13.28	14.74	13.01	14.69	15.35
Sep	7.52	6.97	8.10	8.31	10.03	11.29	13.86	13.73	13.56	14.15	
Oct	7.82	7.00	7.95	8.67	10.05	11.04	13.82	13.48	14.13	14.79	
Nov	7.41	7.11	8.12	8.90	10.18	11.08	14.45	14.10	13.70	13.87	
Dec	7.41	6.62	8.09	8.46	10.50	11.57	15.48	13.74	12.37	14.36	
Average	8.31	7.31	7.25	8.20	9.75	10.87	12.94	14.87	13.29	13.29	14.31

Figure B. 17: The exchange rates used in S-BEAT are found in the Lists tab and can be adjusted

- The CAPEX is now calculated, steps 3 to 7 must be repeated for the intermediate and final products if required

B.5. OPEX sheet

1. The raw material costs are only calculated for the initial product. The user can use the default values for the raw material cost, or the user can enter their own raw material price per ton. If a user value is not entered, then the default values will be used. (See Figure B. 18)

Section 1.1 : Raw Material Costs

Raw Material Quantity (t/h):

Raw Material Price (R/t):

or

Enter a Price (R/t):

Raw Material Cost (t/d):

Raw Material Cost (t/a):

Raw Material Cost (R/a):

Figure B. 18: The raw material costs calculation, if a price is not entered then the default values are used

2. The user must enter information to obtain labour costs. The user must select the operating labour costing button, and either uses the default values or enter user values for the salaries and the shifts per day (See Figure B. 19)

Salaries

Page 1

Select the default salary scales or enter known salaries/month for the following job descriptions

Select an Option
 Default Values Enter Values Shifts per day:

Job Description	Salary / month	Number of Employees
Plant Manager		
Process Engineer		
Admin Clerk		
Secretary		
Equipment Operators		

Cancel Finish

Figure B. 19: Enter values for the salaries per month or select to use the default values

3. The number of equipment operators is calculated for the operating labour by first selecting the change equipment list button. The user must choose the major equipment that is available in the new plant. They must then select the equipment

items from the list and then click on the add to list button. When all the equipment is added, the user must click finish. (See Figure B. 20). The finish button populates the equipment list to the spreadsheet along with the number of units per operator. The user must then specify the number of equipment units by entering values on the spreadsheet (See Figure B. 21)

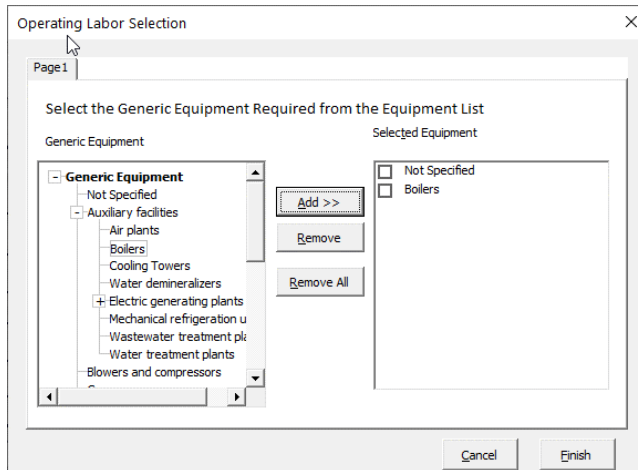


Figure B. 20: Selecting major equipment for the plant from the generic equipment list

Major Equipment	Number of Units	Operators/ Unit	Operators/ shift
Conveyors	4	0.1	0.4
Mixers	2	0.13	0.26
Reactors	5	0.25	1.25
Towers, including auxiliary pumps and exchangers	1	0.25	0.25
Evaporators	1	0.15	0.15
Heat exchangers	9	0.05	0.45

Figure B. 21: The user must enter the number of units which corresponds to the major equipment

- Figure B. 22 shows the OPEX calculation. If required, the user can adjust the factors that are used.

Item	Factor	Factor Basis	Cost
Raw Materials	-	Section 1.1	357 483 056
Miscellaneous Materials	0.1	of Maintenance	13 620 131
Utilities	0.1	of TPC	66 514 905
Waste Management	0.03	of TPC	19 954 471
Variable Cost of Production			457 572 564
Maintenance	0.05	of FCI	136 201 311
Operating Labor	-	Section 1.2	1 184 706
Laboratory Costs	0.2	of Operating Labour	236 941
Supervision	0.2	of Operating Labour	236 941
Major Salaries	-	Section 1.2	1 998 720
Plant Overheads	0.48	of Operating Labour	568 659
Capital Charges	0.00	of FCI	0
Insurance	0.005	of FCI	13 620 131
Royalties	0.005	of FCI	13 620 131
Fixed Cost of Production			167 667 541
Direct Production Cost			625 240 105
Sales Expense	0.02	of TPC	13 302 981
General Overheads	0.02	of TPC	13 302 981
Research and Development	0.02	of TPC	13 302 981
General Expenses			39 908 943
Total Production Cost (TPC)			665 149 048

Figure B. 22: The OPEX is calculated by applying factors to either the maintenance value, fixed capital investment or the total production costs

- Steps 2 to 4 must be repeated in the intermediate and final product sections if required to conclude the OPEX calculation sheet.

B.6. Economics sheet

- The user must first select which product they want the discounted cash flow to evaluate. The values that are required by the discounted cash flow will be populated depending on which option button is selected. A selling price for the corresponding product must also be input. (See Figure B. 23)

Select which Product to Evaluate	Enter Selling Price
<input checked="" type="radio"/> INITIAL PRODUCT	26000
<input type="radio"/> INTERMEDIATE PRODUCT	16622
<input type="radio"/> FINAL PRODUCT	40000

Figure B. 23: Select the product to be evaluated and enter the corresponding selling prices

- The inflation rates, discount rate, and income tax rate values that are required by the discounted cash flow can be entered, or the default values can be used. If inflation is not needed, then a value of 0 can be specified (See Figure B. 24)

Discounted Cash Flow Analysis				
Please Specify the following or use the default values:			Default	USER
Construction inflation rate	0.00	fraction/year	0.00	
Product price inflation rate	0.04	fraction/year	0.035	
Total production cost inflation rate	0.01	fraction/year	0.01	
Discount Rate (annual-compounding)	0.20	fraction/year	0.20	
Discount Rate (Continuous-Compounding)	0.18	fraction/year	0.182	
Income Tax Rate	0.28	fraction/year	0.28	

Figure B. 24: Values required by the DCF must be specified

- The user can specify a depreciation method for the discounted cash flow. Either the straight-line depreciation or the Modified Accelerated Cost Recovery System method

can be used. If the user selects the straight-line depreciation method, then they must input a period for the depreciation. If the MARCS method is selected, then this can be left blank. The user must select the method with the option button and then click on the green button for the correct values to be populated to the discounted cash flow. (See Figure B. 25)

Select a Depreciation Method & Click Button	
<input checked="" type="radio"/> STRAIGHT LINE METHOD	<input type="radio"/> MARCS METHOD

Depreciation	
Period	25
Salvage Value	0
Dep Rate	0.04
	108 961 049

Figure B. 25: The user can select between two depreciation methods

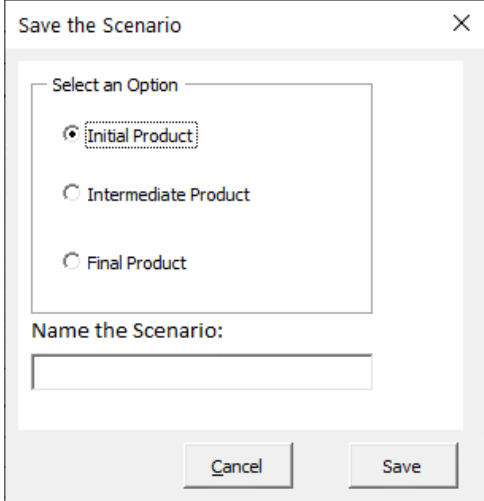
- The discounted cash flow is calculated, and the Net Present Value, Internal Rate of Return and discounted and simple payback periods can be analysed. (See Figure B. 26)

Case Results	
IRR (%)	27.855
NPV (R)	R 1 830 785 719
PBP (Years)	7
PBP Straight	4

Figure B. 26: The NPV, IRR, and payback period results are obtained from the DCF calculation

B.7. Scenario Analysis sheet

- The scenario analysis sheet allows the user to save any of the case studies that are run in S-BEAT. It is specifically used to allow for comparisons between different cases, which can be done in the *Results* sheet. This capability is also useful as it provides a good record of the previously used values and previously generated results.
- Once the user has been through the design specs, literature specs, CAPEX, OPEX and Economics sheets, they may proceed to the scenario analysis sheet. A scenario is saved by clicking on the *Save Scenario* button. A pop-up box will appear, and the user must select whether they want to save the initial product scenario, intermediate product scenario or the final product scenario. (See Figure B. 27) The user must then name the scenario; the scenario name will be the column headings in the scenario analysis table. The user can simply delete the column if they wish to delete a scenario.



Save the Scenario

Select an Option

Initial Product

Intermediate Product

Final Product

Name the Scenario:

Cancel Save

Figure B. 27: The user must select which product scenario they want to save, and they must name the scenario

3. Every parameter that is used in S-BEAT is saved to the scenario analysis table as can be seen in Figure B. 28.

	A	P	Q	R	S	T	U
16	Save Scenario						
17							
18							
19							
20	Parameters	Succinic Acid Hig	Succinic Acid Low	BDO High	BDO Low	BDO Base	EtoH Base
21	Case Study						
22	Product Number						
23	Feed Source:	Sugarcane	Sugarcane				Sugarcane
24	Mill Model:	Yes	Yes				Yes
25	Stream Name:	Clear Juice	Clear Juice				Clear Juice
26	Season Start:	2016/03/30	2016/03/30	2016/03/30	2016/03/30	2016/03/30	2016/03/30
27	Season End:	2016/12/07	2016/12/07	2016/12/07	2016/12/07	2016/12/07	2016/12/07
28	Plant Operational Hours	24.00	24.00	24.00	24.00	24.00	24.00
29	Main Reaction	7 C6H12O6 + 6 CO2	7 C6H12O6 + 6 CO2	1 C4H6O4 + 4 H2	1 C4H6O4 + 4 H2	1 C4H6O4 + 4 H2	1 C6H12O6 → 2 C2
30	Reactor Conversion	94.00	94.00	90.00	90.00	90.00	90.00
31	Separation Recovery	95.00	95.00	99.50	99.50	99.50	99.70
32	Product Quantity tph	17.07	17.07	11.66	11.66	11.66	7.80
33	Data Source:	Literature Process Des	Literature Process Design	Literature Process Design	Literature Process Design	Literature Process Design	Literature Process Design
34	Data Reference:	Intratec Solutions	Intratec Solutions	Intratec Solutions	Intratec Solutions	Intratec Solutions	Virtual Sugarcane Biore
35	Plant Product:	Succinic Acid	Succinic Acid	1,4-BDO	1,4-BDO	1,4-BDO	Ethanol
36	Designing a Similar Plant:	Yes	Yes	Yes	Yes	Yes	Yes
37	Ref Plant Year:	2 014.00	2 014.00	2 013.00	2 013.00	2 013.00	2 014.00
38	Ref Plant Location:	United States	United States	United States	United States	United States	Brazil
39	Ref Product Capacity:	77 000.00	77 000.00	55 000.00	55 000.00	55 000.00	84 001.42
40	Ref Plant Capital Cost:	260 000 000.00	260 000 000.00	100 000 000.00	100 000 000.00	100 000 000.00	32 840 829.88
41	New Plant Year	2 019.00	2 019.00	2 019.00	2 019.00	2 019.00	2 019.00
42	New Plant Location	South Africa	South Africa	South Africa	South Africa	South Africa	South Africa
43	User Location Factor	1.40	1.40	1.40	1.40	1.40	1.40
44	User SA Location Factor	1.20	1.20	1.20	1.20	1.20	1.20
45	Location Factor	85.60	85.60	85.60	85.60	85.60	85.60
46	SA Location Factor	60.80	60.80	60.80	60.80	60.80	60.80
47	Eynonnet Tyne	0.67	0.67	0.67	0.67	0.67	0.67
49	WCI Factor	0.10	0.10	0.10	0.10	0.10	0.10
50	Shifts per day	3.00	3.00	3.00	3.00	3.00	3.00
51	Plant Manager	283 536.00	283 536.00	283 536.00	283 536.00	283 536.00	283 536.00
52	Process Engineer	229 032.00	229 032.00	229 032.00	229 032.00	229 032.00	229 032.00
53	Admin Clerk	85 788.00	85 788.00	85 788.00	85 788.00	85 788.00	85 788.00
54	Secretary	117 864.00	117 864.00	117 864.00	117 864.00	117 864.00	117 864.00
55	Equipment Operators	131 634.00	131 634.00	131 634.00	131 634.00	131 634.00	131 634.00
56	# Plant Manager	3.00	3.00	3.00	3.00	3.00	3.00
57	# Process Engineer	3.00	3.00	3.00	3.00	3.00	3.00
58	# Admin Clerk	4.00	4.00	4.00	4.00	4.00	4.00
59	# Secretary	1.00	1.00	1.00	1.00	1.00	1.00
60	# Equipment Operators	13.00	13.00	10.00	10.00	10.00	6.00
61	Factor Miscellaneous Material	0.10	0.10	0.10	0.10	0.10	0.10
62	Factor Utilities	0.10	0.10	0.10	0.10	0.10	0.10
63	Factor Waste Management	0.03	0.03	0.03	0.03	0.03	0.03
64	Factor Maintenance	0.05	0.05	0.05	0.05	0.05	0.05
65	Factor Laboratory Costs	0.20	0.20	0.20	0.20	0.20	0.20
66	Factor Supervision	0.20	0.20	0.20	0.20	0.20	0.20
67	Factor Plant Overheads	0.48	0.48	0.48	0.48	0.48	0.48
68	Factor Capital Charges	-	-	-	-	-	-
69	Factor Insurance	0.01	0.01	0.01	0.01	0.01	0.01
70	Factor Royalties	0.01	0.01	0.01	0.01	0.01	0.01
71	Factor Sales Expense	0.02	0.02	0.02	0.02	0.02	0.02
72	Factor General Overheads	0.02	0.02	0.02	0.02	0.02	0.02
73	Factor Research and Developm	0.03	0.03	0.03	0.03	0.03	0.03
75	Product price inflation rate	0.04	0.04	0.04	0.04	0.04	0.04
76	Total production cost inflatio	0.01	0.01	0.01	0.01	0.01	0.01
77	Discount Rate (annual-comp)	0.20	0.20	0.20	0.20	0.20	0.20
78	Discount Rate (Continuous-C	0.18	0.18	0.18	0.18	0.18	0.18
79	Income Tax Rate	0.28	0.28	0.28	0.28	0.28	0.28
80	Price per ton	14 783.04	18 068.16	29 911.12	36 558.04	33 234.58	13 374.77
81	Sucrose flowrate	17.01	17.01				17.01
82	Plant Operational Days	252.00	252.00	252.00	252.00	252.00	252.00
83	New Product Capacity	103 210.10	103 210.10	70 534.74	70 534.74	70 534.74	47 200.39
84	CEPCI Ref	576.10	576.10	567.30	567.30	567.30	576.10
85	CEPCI New	612.70	612.70	612.70	612.70	612.70	612.70
86	CEPCI Year	2 018.00	2 018.00	2 018.00	2 018.00	2 018.00	2 018.00
87	WCI Adj	26 000 000.00	26 000 000.00	10 000 000.00	10 000 000.00	10 000 000.00	3 284 082.99
88	FCI Adj	234 000 000.00	234 000 000.00	90 000 000.00	90 000 000.00	90 000 000.00	29 556 746.89
89	Capacity Adjusted Cost	284 748 179.56	284 748 179.56	106 323 574.23	106 323 574.23	106 323 574.23	17 593 397.12
90	Time Adjusted Cost	302 838 412.80	302 838 412.80	114 832 458.89	114 832 458.89	114 832 458.89	18 711 116.85
91	Location Adjusted Cost	215 100 181.05	215 100 181.05	81 563 241.83	81 563 241.83	81 563 241.83	19 119 931.17
92	FCI corrected	225 855 190.11	225 855 190.11	85 641 403.92	85 641 403.92	85 641 403.92	20 075 927.73
93	WCI USD	22 585 519.01	22 585 519.01	8 564 140.39	8 564 140.39	8 564 140.39	2 007 592.77
94	TCI USD	248 440 709.12	248 440 709.12	94 205 544.31	94 205 544.31	94 205 544.31	22 083 520.50
95	Exchange Rate	13.29	13.29	13.29	13.29	13.29	13.29
96	Fixed Capital Investment	3 302 729 380.22	2 702 233 129.27	1 252 352 805.15	1 024 652 295.13	1 138 502 550.14	266 886 037.22
97	Working Capital Investment	300 248 125.47	300 248 125.47	113 850 255.01	113 850 255.01	113 850 255.01	26 688 603.72
98	Total Capital Investment	3 602 977 505.70	3 002 481 254.75	1 366 203 060.17	1 138 502 550.14	1 252 352 805.15	293 574 640.95
99	Juice Quantity	148 01	148 01				148 01
100	Juice Cost Hr	3 332.24	3 332.24				3 332.24
101	Juice Cost D	895 164.48	895 164.48				895 164.48
102	Juice Cost Ann	395 010 050.56	263 340 033.71				329 175 042.14
103	Operators_salary	1 711 242.00	1 711 242.00	1 316 340.00	1 316 340.00	1 316 340.00	789 804.00
104	Operators_salaries	3 709 962.00	3 709 962.00	3 315 060.00	3 315 060.00	3 315 060.00	2 788 524.00
105	Raw Material Cost	395 010 050.56	263 340 033.71				329 175 042.14
107	Miscellaneous Materials	16 513 646.90	13 511 165.65	6 261 764.03	5 123 261.48	5 692 512.75	1 334 430.19
108	Utilities	75 913 989.54	54 839 634.82	10 602 021.18	8 774 794.86	9 688 408.02	43 210 640.26
109	Waste Management	22 774 196.86	16 451 890.45	3 180 606.35	2 632 438.46	2 906 522.41	12 963 192.08
110	Variable Cost of Production	510 211 883.86	348 142 724.63	20 044 391.56	16 530 494.80	18 287 443.18	386 683 304.66
111	Maintenance	165 136 469.01	135 111 656.46	62 617 640.26	51 232 614.76	56 925 127.51	13 344 301.86
112	Operating Labour Cost	1 711 242.00	1 711 242.00	1 316 340.00	1 316 340.00	1 316 340.00	789 804.00
113	Laboratory Costs	342 248.40	342 248.40	263 268.00	263 268.00	263 268.00	157 960.80
114	Supervision	342 248.40	342 248.40	263 268.00	263 268.00	263 268.00	157 960.80
115	Major Salaries Cost	1 998 720.00	1 998 720.00	1 998 720.00	1 998 720.00	1 998 720.00	1 998 720.00
116	Plant Overheads	821 396.16	821 396.16	631 843.20	631 843.20	631 843.20	379 105.92
117	Capital Charges						
118	Insurance	16 513 646.90	13 511 165.65	6 261 764.03	5 123 261.48	5 692 512.75	1 334 430.19
119	Royalties	16 513 646.90	13 511 165.65	6 261 764.03	5 123 261.48	5 692 512.75	1 334 430.19
120	Fixed Cost of Production	203 379 617.77	167 349 842.72	79 614 607.51	65 952 576.91	72 783 592.21	19 496 713.75
121	Sales Expense	15 182 797.91	10 967 926.96	2 120 404.24	1 754 958.97	1 937 681.60	8 642 128.05
122	General Overheads	15 182 797.91	10 967 926.96	2 120 404.24	1 754 958.97	1 937 681.60	8 642 128.05
123	Research and Development	15 182 797.91	10 967 926.96	2 120 404.24	1 754 958.97	1 937 681.60	8 642 128.05
124	General Expenses	45 548 393.72	32 903 780.89	6 361 212.71	5 264 876.92	5 813 044.81	25 926 384.15
127	IRR_SA	19.16	31.21	21.00	32.66	26.49	48.61
128	PBP	25.00	6.00	17.00	5.00	8.00	3.00
129	Fraction Diverted	0.50	0.50				0.50
130	Annual Sales	R1 525 759 096.87	R1 864 816 673.95	R2 109 773 237.90	R2 578 611 735.21	R2 344 192 486.55	R631 294 560.24
131	Project Lifetime	25.00	25.00	25.00	25.00	25.00	25.00

Figure B. 28: The scenario analysis table saves every parameter that is used in S-BEAT and every result that is generated

B.8. Sensitivity Analysis sheet

1. A sensitivity analysis can be done on specific parameters in S-BEAT. This capability is available for the initial product (See Figure B. 29), the intermediate product (See Figure B. 30) and the final product (See Figure B. 31). The user must enter a negative sign to specify a decrease in the parameter else S-BEAT assumes a positive change to the parameter. After each change is made, a scenario should be saved in the scenario analysis sheet.

Initial Product																																																					
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Figure B. 29: The variables that a sensitivity analysis can be performed on for the initial product

Intermediate Product																																									
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Vary in Initial Product																																									

Figure B. 30: The variables that a sensitivity analysis can be performed on for the intermediate product

Final Product																																							
<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="text-align: left;">Design Specification Parameters</th> <th style="text-align: left;">Varying by:</th> </tr> </thead> <tbody> <tr> <td>Reactor Conversion</td> <td><input type="text" value="0%"/></td> </tr> <tr> <td>Separation Recovery</td> <td><input type="text" value="0%"/></td> </tr> <tr> <td>Product Quantity</td> <td><input type="text" value="0%"/></td> </tr> </tbody> </table> <table border="1" style="width: 100%; border-collapse: collapse; margin-top: 5px;"> <thead> <tr> <th style="text-align: left;">Literature Specification Parameters</th> <th style="text-align: left;">Varying by:</th> </tr> </thead> <tbody> <tr> <td>Plant Location Factor</td> <td><input type="text" value="0%"/></td> </tr> </tbody> </table> <table border="1" style="width: 100%; border-collapse: collapse; margin-top: 5px;"> <thead> <tr> <th style="text-align: left;">CAPEX</th> <th style="text-align: left;">Varying By:</th> </tr> </thead> <tbody> <tr> <td>CEPCI</td> <td><input type="text" value="0%"/></td> </tr> <tr> <td>Working Capital Factor</td> <td><input type="text" value="0%"/></td> </tr> <tr> <td>Contingency Factor</td> <td><input type="text" value="0%"/></td> </tr> <tr> <td>FCI</td> <td><input type="text" value="0%"/></td> </tr> </tbody> </table>	Design Specification Parameters	Varying by:	Reactor Conversion	<input type="text" value="0%"/>	Separation Recovery	<input type="text" value="0%"/>	Product Quantity	<input type="text" value="0%"/>	Literature Specification Parameters	Varying by:	Plant Location Factor	<input type="text" value="0%"/>	CAPEX	Varying By:	CEPCI	<input type="text" value="0%"/>	Working Capital Factor	<input type="text" value="0%"/>	Contingency Factor	<input type="text" value="0%"/>	FCI	<input type="text" value="0%"/>	<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="text-align: left;">OPEX Parameters</th> <th style="text-align: left;">Varying by:</th> </tr> </thead> <tbody> <tr> <td>Number of Equipment Operators</td> <td><input type="text" value="0%"/></td> </tr> <tr> <td>Total Operating Labour Salary</td> <td><input type="text" value="0%"/></td> </tr> <tr> <td>Salaries</td> <td><input type="text" value="0%"/></td> </tr> <tr> <td>DPC</td> <td><input type="text" value="0%"/></td> </tr> <tr> <td>FPC</td> <td><input type="text" value="0%"/></td> </tr> <tr> <td>Utilities Factor</td> <td><input type="text" value="0%"/></td> </tr> </tbody> </table> <table border="1" style="width: 100%; border-collapse: collapse; margin-top: 5px;"> <thead> <tr> <th style="text-align: left;">Economics</th> </tr> </thead> <tbody> <tr> <td>Vary in Initial Product</td> </tr> </tbody> </table>	OPEX Parameters	Varying by:	Number of Equipment Operators	<input type="text" value="0%"/>	Total Operating Labour Salary	<input type="text" value="0%"/>	Salaries	<input type="text" value="0%"/>	DPC	<input type="text" value="0%"/>	FPC	<input type="text" value="0%"/>	Utilities Factor	<input type="text" value="0%"/>	Economics	Vary in Initial Product
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Economics																																							
Vary in Initial Product																																							

Figure B. 31: The variables a sensitivity analysis can be performed on for the final product

2. The user can either change one parameter at a time and save the scenario (as required for a tornado plot) or change multiple parameters at a time and group them under high or low-risk scenarios.
3. When analysing the effects of the final product (e.g.) the user should input a value for the same variable in the initial, intermediate, and final product sections as the changes will be implemented to each parameter in their corresponding sections in the program. This is required as the final number is a summation of the three separate calculations, for example, the fixed capital investment of the final plant is a summation of the initial, intermediate, and final product fixed capital investments. If the sensitivity analysis is done to increase the FCI by 10%, then 10% must be input in the FCI block for the initial, intermediate, and final product sections.

B.9. Results sheet

1. The user can select from the saved scenarios to show a product summary. (See Figure B. 32)

Product Summary																																																									
<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="text-align: left;">Select the Product</th> <th style="text-align: left;">FDCA Base Syrup</th> </tr> </thead> <tbody> <tr> <td>Raw Material Stream</td> <td>Syrup</td> </tr> <tr> <td>Raw Material Stream Diverted</td> <td>Syrup</td> </tr> <tr> <td>Raw Material Capacity</td> <td>180 502,56</td> </tr> <tr> <td>Product Capacity</td> <td>50 279,30</td> </tr> <tr> <td>Total Capital Investment</td> <td>1 958 231 161</td> </tr> <tr> <td>Total Production Cost</td> <td>590 632 804</td> </tr> <tr> <td>Product Price</td> <td>20 148</td> </tr> <tr> <td>Product Sales Revenue</td> <td>Syrup</td> </tr> <tr> <td>Net Present Value</td> <td>41 124 798</td> </tr> <tr> <td>MARR</td> <td>0,20</td> </tr> <tr> <td>IRR</td> <td>2027,95</td> </tr> <tr> <td>Project Lifetime</td> <td>Syrup</td> </tr> <tr> <td>Discounted Payback Period</td> <td>22</td> </tr> </tbody> </table>	Select the Product	FDCA Base Syrup	Raw Material Stream	Syrup	Raw Material Stream Diverted	Syrup	Raw Material Capacity	180 502,56	Product Capacity	50 279,30	Total Capital Investment	1 958 231 161	Total Production Cost	590 632 804	Product Price	20 148	Product Sales Revenue	Syrup	Net Present Value	41 124 798	MARR	0,20	IRR	2027,95	Project Lifetime	Syrup	Discounted Payback Period	22	<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="text-align: left;">Select the Product</th> <th style="text-align: left;">Lactic Acid Base</th> </tr> </thead> <tbody> <tr> <td>Raw Material Stream</td> <td>Syrup</td> </tr> <tr> <td>Raw Material Stream Diverted</td> <td>Syrup</td> </tr> <tr> <td>Raw Material Capacity</td> <td>180 502,56</td> </tr> <tr> <td>Product Capacity</td> <td>81 318,89</td> </tr> <tr> <td>Total Capital Investment</td> <td>1 880 665 083</td> </tr> <tr> <td>Total Production Cost</td> <td>584 057 661</td> </tr> <tr> <td>Product Price</td> <td>17 220</td> </tr> <tr> <td>Product Sales Revenue</td> <td>Syrup</td> </tr> <tr> <td>Net Present Value</td> <td>1 819 135 574</td> </tr> <tr> <td>MARR</td> <td>0,20</td> </tr> <tr> <td>IRR</td> <td>3193,01</td> </tr> <tr> <td>Project Lifetime</td> <td>Syrup</td> </tr> <tr> <td>Discounted Payback Period</td> <td>6</td> </tr> </tbody> </table>	Select the Product	Lactic Acid Base	Raw Material Stream	Syrup	Raw Material Stream Diverted	Syrup	Raw Material Capacity	180 502,56	Product Capacity	81 318,89	Total Capital Investment	1 880 665 083	Total Production Cost	584 057 661	Product Price	17 220	Product Sales Revenue	Syrup	Net Present Value	1 819 135 574	MARR	0,20	IRR	3193,01	Project Lifetime	Syrup	Discounted Payback Period	6
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Figure B. 32: A product summary is generated by selecting a saved scenario from the drop-down list

2. The user can select, from drop-down lists, the saved base cases from the scenario analysis sheet to display either an IRR or an NPV plot or both the IRR and NPV on

one graph. This can be done for up to 10 scenarios. (See Figure B. 33) An example of the resulting graph is shown in Figure B. 34.

	NPV	IRR	PBP
Lactic Acid Base	1 819	31.93	6
PLA Base	1 319	26.47	8
Succinic Acid Base	1 227	24.90	10
BDO Base	2 253	26.49	8
EtOH Base	847	48.61	3
ETE Base	416	12.41	25
MEG Base	864	26.13	9
FDCA Base Syrup	41	20.28	22
Lysine Syrup Base	1 831	27.86	7

Figure B. 33: The user can select to view and IRR or NPV plot for any saved scenarios

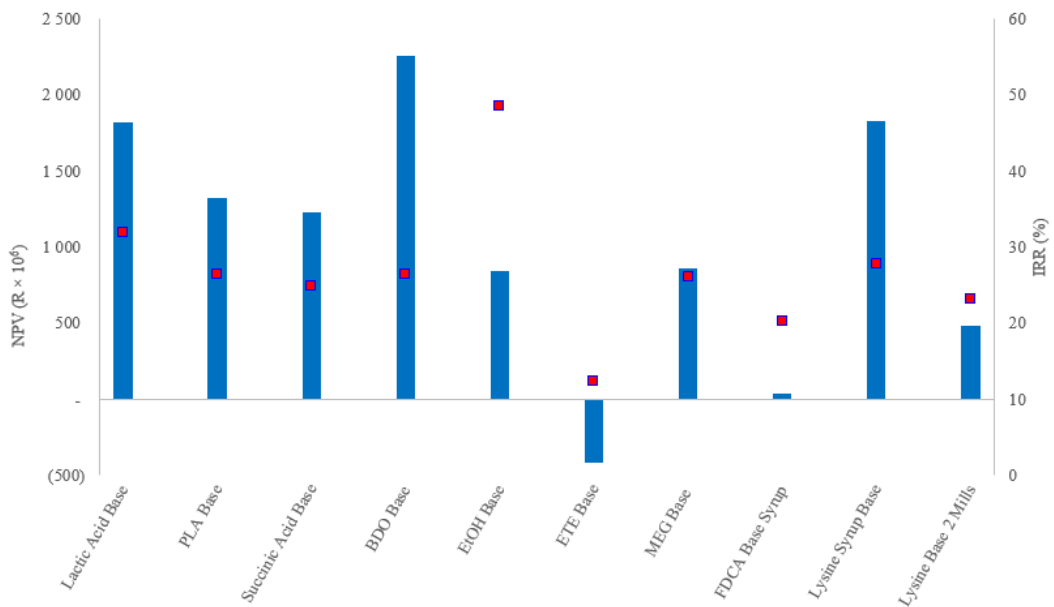


Figure B. 34: A visual of the graph that is obtained from selecting to plot an IRR or NPV graph

- The user can select the IRR and/or the NPV for different mill streams and their low, high, or base cases from the saved scenario's. (See Figure B. 35) These scenarios are obtained by running a sensitivity analysis. An example of the resulting graph is shown in Figure B. 36.

1. Select the products from the saved scenarios	2. Enter the Name of the Product to be displayed on the chart	3. Don't change the order of the scenarios, rather select the scenario that matches in 1	4. Select to display either the NPV or IRR or Both
1. Lysine Syrup Low 2. Lysine Syrup Base 3. Lysine Syrup High 4. FDCA Low Syrup 5. FDCA Base Syrup 6. FDCA High Syrup	Lysine-Syrup FDCA-Syrup	Low Base High Low Base High	IRR NPV

Figure B. 35: The results of a sensitivity analysis can be graphed in this section

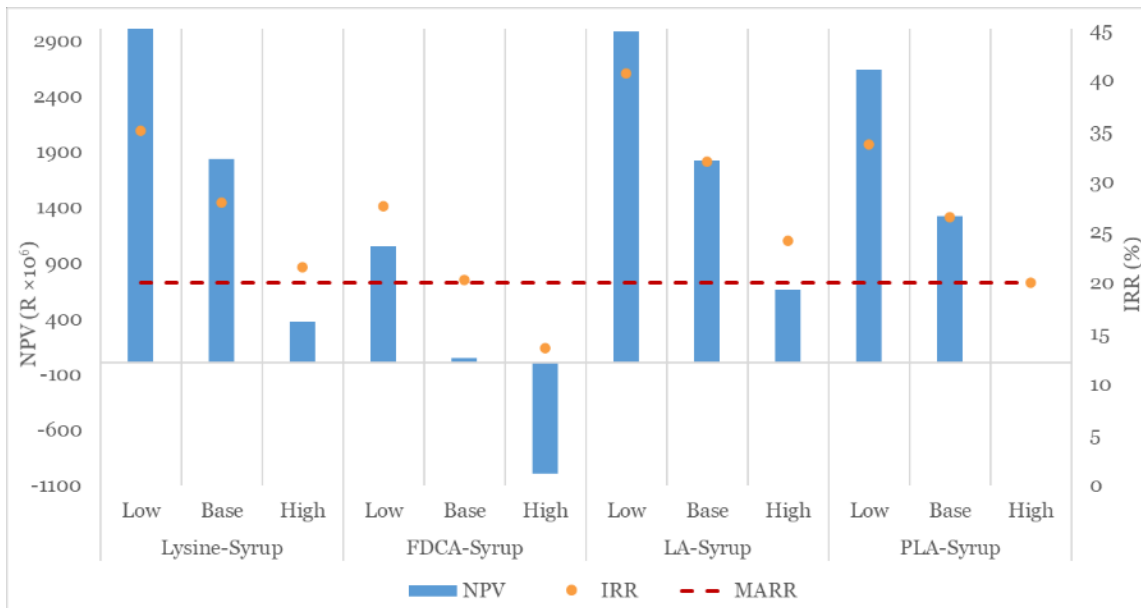


Figure B. 36: The following graph will present the results of the sensitivity analysis (Naidoo *et al.*, 2019)

- The user can automatically plot a tornado plot. First, the user must use the sensitivity analysis to vary a parameter like the FCI, raw material price and selling price. The base case, a minimum case and a maximum case must be run whilst saving the scenarios after each case. The user must then select the parameter that was varied from the drop-down list, as shown in Figure B. 37 as well as select the scenarios that were run (also shown in Figure B. 37). Figure B. 38 and Figure B. 39 shows an example of the set up for the tornado plot and the resulting tornado plot, respectively.

1. Select the scenarios from the scenario analysis whereby you varied a parameter for the 2. Name the product

	Minimum	Base	Maximum
Lysine-A-1	Lysine 2 Mills 10 FCI	Lysine Base 2 Mills	Lysine 2 Mills -10 FCI
	Lysine 2 Mills -20 RM	Lysine Base 2 Mills	Lysine 2 Mills 20 RM
	Lysine 2 Mills -10 SP	Lysine Base 2 Mills	Lysine 2 Mills 10 SP
	MEG -10 FCI	MEG Base	MEG +10 FCI
	MEG -20 RM	MEG Base	MEG CJ +20 RM

Figure B. 37: The parameters that can be varied in the sensitivity analysis are selected together with their corresponding cases

1. Select the scenarios from the scenario analysis whereby you varied a parameter for the		2. Name the product		
		Minimum	Base	Maximum
Lysine-A-mol	FCI	Lysine 2 Mills 10 FCI	Lysine Base 2 Mills	Lysine 2 Mills -10 FCI
	Raw Material Price	Lysine 2 Mills -20 RM	Lysine Base 2 Mills	Lysine 2 Mills 20 RM
	Sales Price	Lysine 2 Mills -10 SP	Lysine Base 2 Mills	Lysine 2 Mills 10 SP
MEG - CJ	FCI	MEG -10 FCI	MEG Base	MEG +10 FCI
	Raw Material Price	MEG -20 RM	MEG Base	MEG CJ +20 RM
	Sales Price	MEG CJ -10 SP	MEG Base	MEG CJ +10 SP
Lysine-A-mol	FCI	SA -10 FCI	Succinic Acid Base	SA +10 FCI
	Raw Material Price	SA -20 RM	Succinic Acid Base	SA +20 RM

Figure B. 38: The final set up for the tornado plot

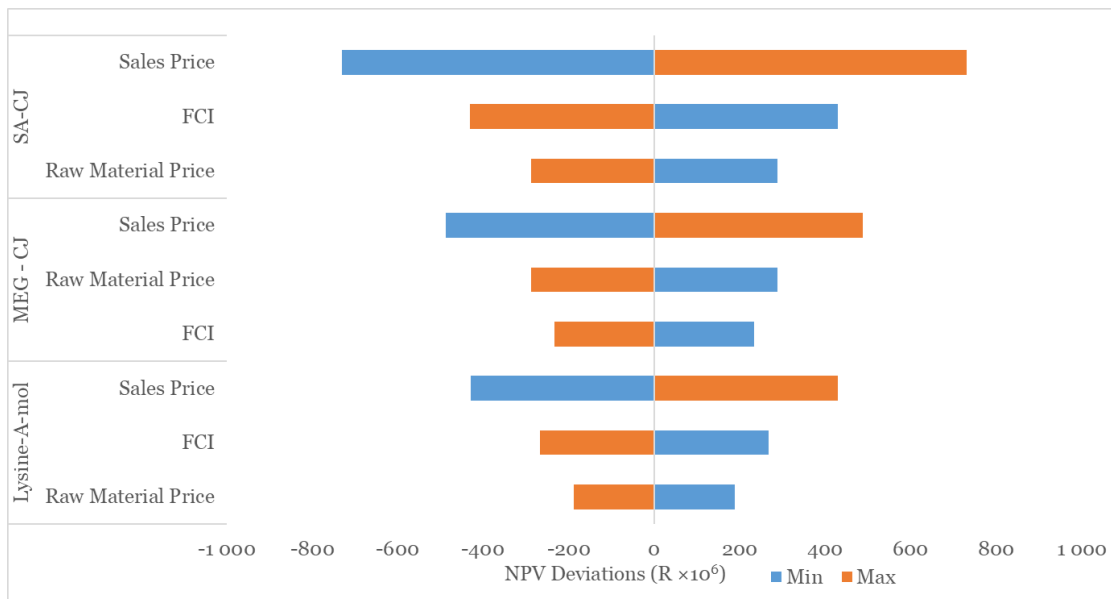


Figure B. 39: How a tornado plot would look for the scenarios depicted in Figure B. 38 (Naidoo et al., 2019)

- The user can also plot an overall feasibility chart. The user must enter the name of the product; this name will appear on the chart as a tag. The user must then select the low-risk case, base case scenario and the high-risk case scenario as generated by the sensitivity analysis and saved to the scenario analysis table (See Figure B. 40). The NPV, IRR and payback period for the corresponding cases are populated and if the $NPV > 0$ then S-BEAT determines that the case is feasible. The user can change the feasibility criteria to either $IRR > MARR$ or $Payback\ Period > \text{the number of years}$. The bubble colour is then determined to be either green, orange, yellow or red (See Figure B. 41 and Figure B. 42). The user is required to change the bubble colour on the graph manually. An example of an overall feasibility chart is shown in Figure (See Figure B. 43).

Overall Feasibility Graph		
		Select Product
LA-Syrup	Low	Lactic Acid Low
	Base	Lactic Acid Base
	High	Lactic Acid High

Figure B. 40: Selecting the scenarios to represent the base, low-risk, and high-risk cases for the feasibility plot

		NPV	IRR	PBP	No is unfeasible case Yes is feasible case	Bubble Colour
LA-Syrup	Low	2979.40	40.63	4	Yes	Green
	Base	1819.14	31.93	6	Yes	
	High	658.87	24.12	11	Yes	

Figure B. 41: The feasibility plot bubble colour is determined based on user-defined criteria of the NPV, IRR or payback period

Bubble Colour	Scenario is feasible (Yes, i.e., NPV>0 or No, i.e., NPV<0)		
	Low-risk case	Base Case	High-risk Case
Green	Yes	Yes	Yes
Orange	Yes	Yes	No
Yellow	Yes	No	No
Red	No	No	No

Figure B. 42: An example of the criteria that determine the bubble colour (with regards to the NPV) in the feasibility plot

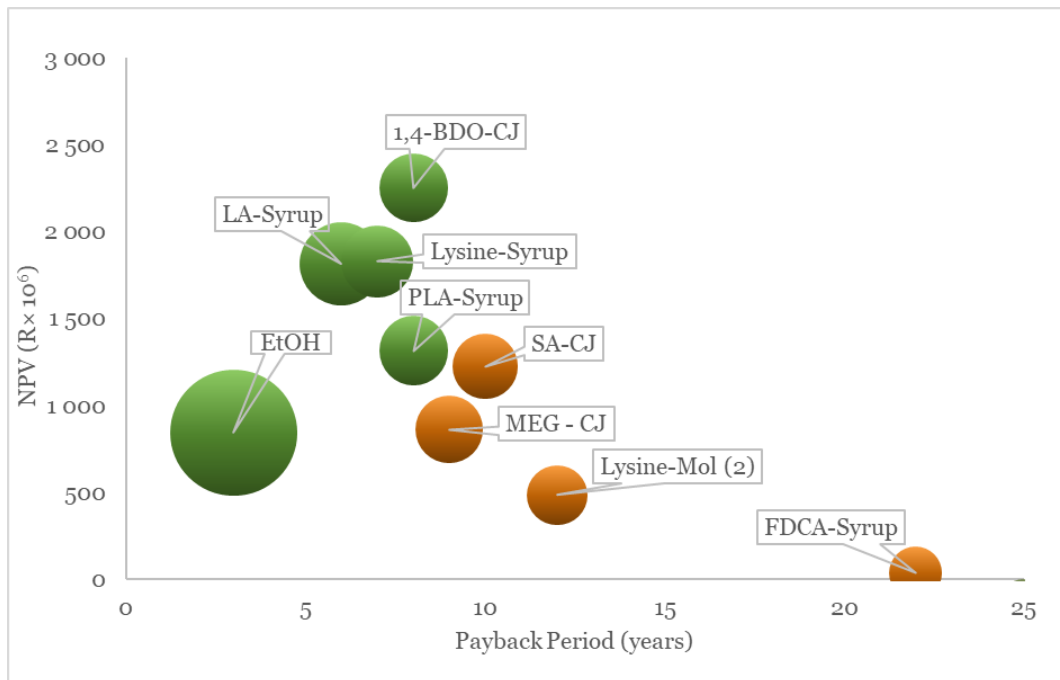


Figure B. 43: An example of the generated feasibility plot (Naidoo *et al.*, 2019)

B.10. Additional analysis

1. An additional feature was added to S-BEAT as per chapter 3, i.e., the automated generation of minimum selling price plots for a range of feedstock costs and multiple plant capacities.
2. The additional analysis sheet has five tables, where each table represents a different plant capacity. Next to each table is set of input boxes, the user is required to specify an initial raw material cost, a raw material cost interval, the minimum acceptable rate of return that the plant should achieve, an initial guess of the selling price and a percentage of the raw material that is diverted to the biorefinery (new plant capacity). The % diverted is the only variable that changes between tables so that a range of plant capacity lines can be generated. Once the user has input the initial conditions, they must click on the green button. (See Figure B. 44)

Capacity 5		INPUTS				67.85 kt/a OUTPUTS				Capacity 5 Input	
Scenario	%	MARR	Raw Material Cost (R/tonne)	Raw Material Cost (R/tonne Sucrose)	Selling Price	Plant Capacity 5	FCI	TPC	IRR	Starting RMP	RMP Interval
1	50	20	100	179.45						100	250
2	50	20	350	628.08							
3	50	20	600	1076.70							
4	50	20	850	1525.33							
5	50	20	1100	1973.95							
6	50	20	1350	2422.58							
7	50	20	1600	2871.20							
8	50	20	1850	3319.83							
9	50	20	2100	3768.46							
10	50	20	2350	4217.08							
11	50	20	2600	4665.71							
12	50	20	2850	5114.33							
13	50	20	3100	5562.96							
14	50	20	3350	6011.58							
15	50	20	3600	6460.21							
16	50	20	3850	6908.83							
17	50	20	4100	7357.46							
18	50	20	4350	7806.09							
19	50	20	4600	8254.71							
20	50	20	4850	8703.34							

Figure B. 44: Entering input values in the input boxes initialises the table for the minimum selling price plot

3. Various scenarios are run upon clicking the button. The results show the combination of selling prices and feedstock costs for the respective plant capacity, which result in the MARR (See Figure). In other words, if the product of the specific plant capacity with a typical raw material cost is sold at any price higher than the generated minimum selling price, then the plant will have an internal rate of return that is higher than the minimum acceptable rate of return.

Capacity 5		INPUTS				67.85 kt/a OUTPUTS				Capacity 5 Input	
Scenario	%	MARR	Raw Material Cost (R/tonne)	Raw Material Cost (R/tonne Sucrose)	Selling Price	Plant Capacity 5	FCI	TPC	IRR	Starting RMP	RMP Interval
1	50	20	100	179.45	14.685	67.851	2.724 026 228	246 096 208	20.0	100	250
2	50	20	350	628.08	15.361	67.851	2.724 026 228	301 806 874	20.0		
3	50	20	600	1076.70	16.038	67.851	2.724 026 228	357 517 541	20.0		
4	50	20	850	1525.33	16.714	67.851	2.724 026 228	413 228 208	20.0		
5	50	20	1100	1973.95	17.390	67.851	2.724 026 228	468 938 874	20.0		
6	50	20	1350	2422.58	18.067	67.851	2.724 026 228	524 649 541	20.0		
7	50	20	1600	2871.20	18.743	67.851	2.724 026 228	580 360 208	20.0		
8	50	20	1850	3319.83	19.420	67.851	2.724 026 228	636 070 874	20.0		
9	50	20	2100	3768.46	20.096	67.851	2.724 026 228	691 781 541	20.0		
10	50	20	2350	4217.08	20.772	67.851	2.724 026 228	747 492 208	20.0		
11	50	20	2600	4665.71	21.449	67.851	2.724 026 228	803 202 874	20.0		
12	50	20	2850	5114.33	22.125	67.851	2.724 026 228	858 913 541	20.0		
13	50	20	3100	5562.96	22.801	67.851	2.724 026 228	914 624 208	20.0		
14	50	20	3350	6011.58	23.478	67.851	2.724 026 228	970 334 874	20.0		
15	50	20	3600	6460.21	24.154	67.851	2.724 026 228	1 026 045 541	20.0		
16	50	20	3850	6908.83	24.830	67.851	2.724 026 228	1 081 756 208	20.0		
17	50	20	4100	7357.46	25.507	67.851	2.724 026 228	1 137 466 874	20.0		
18	50	20	4350	7806.09	26.183	67.851	2.724 026 228	1 193 177 541	20.0		
19	50	20	4600	8254.71	26.859	67.851	2.724 026 228	1 248 888 208	20.0		
20	50	20	4850	8703.34	27.536	67.851	2.724 026 228	1 304 598 874	20.0		

Figure B. 45: The table is populated with the results of the scenario after the green button is clicked

4. By generating multiple plant capacities, i.e., by populating each table and by entering an average selling price of the product for the year of interest, a graph like that in Figure B. 46 will be generated.

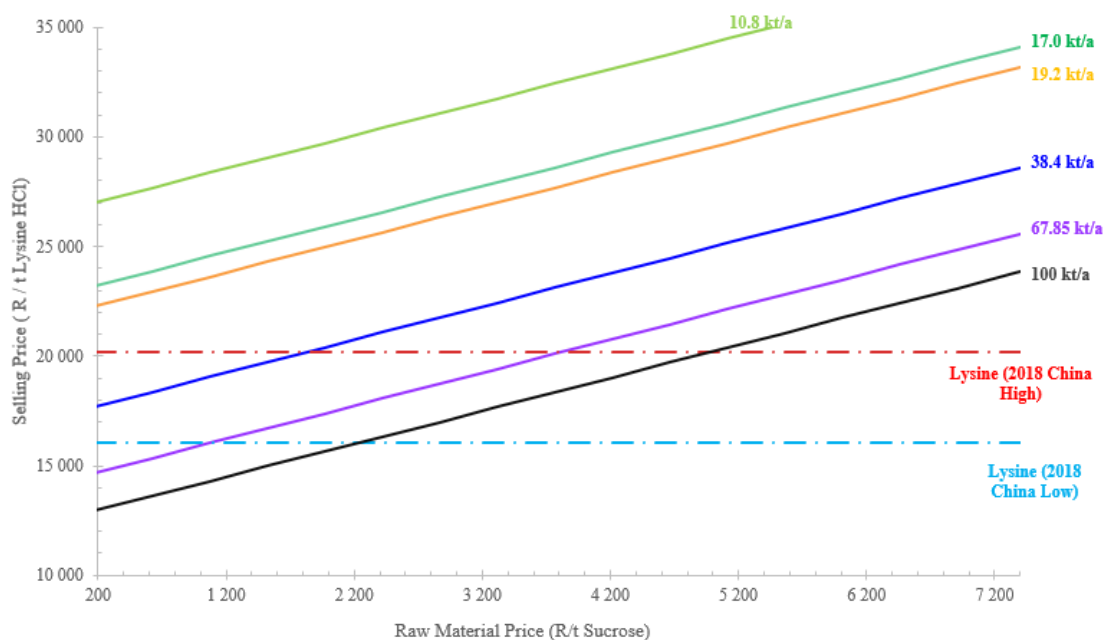


Figure B. 46: An example of a minimum selling price plot for a range of raw material costs and different plant capacities

B.11. Default parameters used in S-BEAT assessments

Table B. 1: Default values used in the CAPEX calculations

CAPEX Factors	Default Value	Comments
CEPCI (2018)	612.7	This was a 2018 preliminary value
CEPCI (2018)	603.1	This final 2018 value should be used in future
WCI _{Ref}	10 %	-
Contingency	5 %	-
WCI _{New}	10 %	-
Exchange rate (2018)	R 13.29	ZAR/US exchange rate
Operating hours	24	-
Operating days	252	-

Table B. 2: Default values used in the OPEX calculations

OPEX Factors	Default Value	Comments
1. Raw materials	-	Calculated value
2. Miscellaneous materials	10 %	of Maintenance
3. Utilities	10 %	of TPC
4. Waste management	3 %	of TPC
5. Variable Production Cost (VPC)		VPC = 1 + 2 + 3 + 4
6. Maintenance	5 %	of FCI
7. Operating labour	-	Calculated value
8. Laboratory costs	20 %	of Operating labour
9. Supervision	20 %	of Operating labour

10. Major salaries	-	Calculated value
11. Plant overheads	48 %	of Operating labour
12. Capital charges	0 %	of FCI
13. Insurance	0.5 %	of FCI
14. Royalties	0.5 %	of FCI
15. Fixed Production Cost (FPC)		FPC = 6 + 7 + 8 + 9 + 10 + 11 + 12 + 13 + 14
16. Direct Production Cost (DPC)		DPC = VPC + FPC
17. Sales Expenses	2 %	of TPC
18. General Overheads	2 %	of TPC
19. Research and Development	2 %	of TPC
20. General Expenses (GE)		GE = 17 + 18 + 19
21. Total Production Costs (TPC)		TPC = DPC + GE

Table B. 3: Default values used in the DCF calculations

DCF Factors	Default Value	Comments
Construction inflation rate	0 %	-
Product price inflation rate	3.5 %	Or set to 0 %
TPC inflation rate	1 %	Or set to 0 %
Minimum Acceptable Rate of Return (MARR)	20 %	Set by the company
Plant lifetime	25 years	Set by the company
Income tax rate	28 %	-
Operating rate	Ramped up	Year 1 = 0.65, Year 2 = 0.9 Year 3 = 1
Depreciation method	MARCs	Year 1=0.4, Year 2 =0.2 Year 3=0.3, Year 4=0.4
	Straight-line	Enter the depreciation period (Default 25 years)