Synthesis of a Sustainable Integrated Pulp and Paper Biorefinery with Strategic Decision Making

Lee Siu Hoong

Bachelor of Engineering (with Honours) in the field of Chemical Engineering

A thesis submitted for the degree of Doctor of Philosophy at Monash University Malaysia in 2016

School of Engineering (Chemical)

Abstract

Sustainable development has emerged as an effective plan towards achieving resource conservation and waste minimization. Sustainability can be realized upon adherence to the triple bottom line, namely economic, environmental and social aspects. In particular, the establishment of an eco-industrial park (EIP) has been regarded as an effective approach to achieve sustainability. An EIP represents an urban industrial area of planned material and energy exchanges among multiple enterprises. This co-sharing initiative allows for a greater reduction in resource consumption and waste generation compared to an enterprise operating unilaterally.

In this research project, it is desired to set up an EIP project for a pulp and paper mill (PPM) with a biorefinery. An integrated pulp and paper biorefinery (IPPB) is introduced, which acts as an EIP comprising of PPM, biorefinery and other potential enterprises. A PPM is chosen as it is a resource intensive industry (i.e. water and energy), while generating large quantity of biomass and waste. The IPPB serves to convert PPM biomass into higher value added bio-products. The main objective of the research is then to synthesize a sustainable IPPB subjected to strategic decision making (SDM) using mathematical optimization techniques.

A SDM framework is necessary as the implementation of any EIP project presents itself as a multiple criteria decision making (MCDM) problem. Often, in any EIP, each enterprise has its own preference towards the optimal EIP scheme, subjected to economic and environmental performance. Besides, the integrated material, energy, economic and environmental networks can be highly interactive, given the high level of participation among the enterprises. Consequently, there would be disagreement on the optimal EIP scheme to be implemented in any given EIP project. This inherent conflict leads to increased competition among enterprises, where each enterprise seeks to protect their self-interest, ultimately rendering the EIP unsustainable.

Thus, a SDM framework is developed which seeks to resolve this inherent competition present among enterprises in an IPPB. Using the proposed framework, it is desired to report a sustainable IPPB which is optimal and agreeable to all enterprises. The framework would account for the preference of each enterprise in an IPPB. At the same time, a mathematical model is formulated which integrates the material, energy and biomass/waste flow among the

enterprises. It is anticipated that the outcome of the proposed work can be applicable to any future EIP project. The developed framework can also be used as a preliminary design and decision making tool to assist an EIP project to achieve sustainability.

Declaration

This thesis contains no material which has been accepted for the award of any other degree or diploma at any university or equivalent institution and that, to the best of my knowledge and belief, this thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

Signature: [redacted] ....

Print Name: **Lee Siu Hoong** ....

Date: **14th November 2016** ....

Acknowledgements

I would like to take this opportunity to express my gratitude to a number of individuals who have helped me throughout my postgraduate study. Firstly, I wish to extend my utmost appreciation to my supervisor, Dr. Irene Chew Mei Leng. She has been an encouraging mentor throughout my course of study and had provided me with both professional and emotional support. I am indebted to her help towards the completion of my thesis.

Next, my deepest appreciation goes to the following academician, Prof. Denny Ng Kok Sum and Prof. Dominic Foo Chwan Yee from The University of Nottingham Malaysia, Associate Prof. Andrew Hoadley from Monash University Australia, Prof. Mahmoud El-Halwagi from Texas A&M University and Prof. Mario Eden from Auburn University. They have been kind enough to host me during my research attachment at their respective universities. Their immense knowledge in their respective research area had been a source of aspiration for me.

Besides, I am also grateful for the help from my fellow research peers which include Leong Yik Teeng, Rex Ng Tong Lip, Wendy Ng and Viknesh Andiappan. It is indeed a pleasure to meet and interact with such a diverse group of individuals. In addition, the completion of my thesis would also have not been possible without the financial support from Monash University Malaysia as well as the 2015 Endeavour Research Fellowship.

Next, a special thank you to my friends, which include (but not limited to) Cathie Lee, Iee Lee, Catherine Chang, Mabel Tan, Cher Pin, Kavitha, Jin Jack, Wee Jun, Chee Yang and Jia Han. Lastly, I wish to express my thanks to the following unique group of individuals, Alan Chin, Julian Tan, Jared Low and Andrew Krishnan (only they would comprehend the significance of this statement).

Publication List

Journal Article

1. Siu Hoong Lee, Rex T. L. Ng, Denny K. S. Ng, Dominic C. Y. Foo, Irene M. L. Chew, (2014), Synthesis of resource conservation networks in an integrated pulp and paper biorefinery, *Industrial and Engineering Chemistry Research*, **53**(25), p. 10417-10428.

Conference Proceedings/Presentations

1. S. H. Lee, Irene M. L. Chew and A. Hoadley, (2016), *An Optimization Approach to Resolve Multiple Decision Making in a Pulp and Paper Biorefinery*, Chemeca Conference, 25 – 28th September 2016, Adelaide Convention Centre, Adelaide, Australia.
2. Lee, S.H., Andiappan, V., Ng, D.K.S. and Chew, I.M.L., (2015), Analysis on the relationship between eco-connectance and economic performance of an eco-industrial park, *Chemical Engineering Transaction*, **45**.
3. S. H. Lee, T. Chandra, Rex T. L. Ng, Denny K. S. Ng, Irene M. L. Chew, (2014), *Synthesis of an Integrated Pulp and Paper Biorefinery with Cogeneration System*, 27th Symposium of Malaysian Chemical Engineers (SOMChE 2014), 29 – 30th October 2014, Taylor's University Lakeside Campus, Selangor, Malaysia.
4. Lee, S.H., Ng, D.K.S. and Chew, I.M.L., (2014), A two-stage optimization approach for the synthesis of an integrated pulp and paper biorefinery, *Energy Procedia*, **61**: p.820-823
5. S. H. Lee, R. T. L. Ng, D. K. S. Ng, D. C. Y. Foo, I. M. L. Chew, (2013), *Optimization of a Gasification-based Integrated Biorefinery for Pulp and Paper Industry*, Proceedings of the 6th International Conference on Process Systems Engineering (PSE Asia), 25 – 27th June 2013, Kuala Lumpur, Malaysia.

Table of Contents

List of Figures

List of Tables

Chapter 1: Introduction

1.1. Overview

1.1.1. Sustainable Development

The concept of sustainable development emerged in the 1980s, defined as "*development that meets the needs of the present generation without compromising the ability of the future generations to meet their own need*" [1]. Within the framework of sustainability, the three interlinking and mutually reinforcing pillar concept is often used, referencing to environment, economic and social. The three pillar concept can be used as a sustainability indicator, where all three pillars are to be satisfied to achieve the sustainability goals of an industry. Resource conservation has been identified as the key to ensure sustainability in the chemical industry. It encompasses the efficient use of resources (e.g. water and energy) to ensure waste minimization through process reuse and recycling. Numerous literatures have been reported to quantify sustainability in the chemical industry. Azapagic and Perdan (2000) reported indicators for all three aspects of sustainability (environmental, economic and social aspects). In their work, environmental indicators are reported based on the impact a process has on the environment [2]. These include global warming potential, ozone depletion potential, acidification potential and many more. Next, economic indicators encompasses financial based indicator and human-capital based indicator. The authors also reported social indicators such as work satisfaction [2]. Later, Ness *et al.* (2007) provided a systematic categorizing of sustainability assessment tools [3]. The authors reported a sustainability framework based on either indicator/indices, product-related assessment or integrated assessment tools. Besides that, further critical reviews of environmental indicators are given by Herva *et al.* (2011), Moldan *et al.* (2012) and Herva and Roca (2013) [4-6].

1.1.2. Eco-Industrial Park

As part of the initiative to achieve sustainable development, the implementation of an eco-industrial park (EIP) could prove to be impactful. An EIP represents a concerted effort among multiple enterprises to share resources (materials, energy, water, etc) and wastes. Through the collaborative efforts among multiple enterprises, greater resource savings can be achieved, resulting in improved economic, environmental and social benefits. The core concept behind the operation of an EIP is known as industrial symbiosis (IS). IS involves the physical exchange or integration of materials (raw material, product, by-product), energy (heat, electricity) and utilities (water) between the different enterprises. The successful introduction of EIPs has been documented in various locations, notably the Kalundborg EIP in Denmark and NISP EIP in UK, which has effectively adhered to the three pillars of sustainability [7-9]. In the past, EIPs emerge spontaneously, through the cooperative initiation among enterprises within the vicinity, in the absence of an external authority involvement (EIP authority). However, seeing the effectiveness of the Kalundborg EIP, the development of EIPs has been studied in other countries such as America, Europe [10], China [11] and Korea [12-14]. The notable difference here is that these proposed EIPs are planned and designed systematically, with the aid of an EIP authority. The EIP authority is often a governmental agencies that have the authority to encourage the formation of EIP and ensure environmental goals are being met [8].

1.1.3. Integrated Pulp and Paper Biorefinery (IPPB)

Globally, the pulp and paper industry is undergoing significant reform and restructuring in its processes. This is partially driven by changing consumer demands towards electronic media over printed media [15]. Pulp and paper mills (PPMs) are one of the most resource intensive industries, consuming large amount of water and energy. Freshwater is commonly used for pulp washing, paper forming and steam generation. Meanwhile, process steam is utilized during the cooking and evaporation process [16, 17]. The efficient management of freshwater and energy is paramount to achieve resource conservation and reduce wastewater generation. As a result, sustainable resource management has been the main agenda in the industry. Current development focuses primarily on enhancing material and energy recovery within the PPM through the incorporation of a biorefinery into its processes. An integrated pulp and paper biorefinery (IPPB) is a sustainable processing facility which converts PPM biomass into value added products such as biofuel and bioenergy [18, 19]. Biomass conversion technology is promising as biofuels are derived from renewable sources unlike conventional fossil fuels. Besides, by using biomass for material and energy recovery, the implementation of biorefineries can assist in the reduction of CO_2 emissions. In PPMs, there are a number of potential biomasses available. These include black liquor, wood residues, wastewater and sludge [20].

1.2. Problem Statement

Pulp and paper mills (PPMs) are recognized as one of the most resource intensive industries, with high consumption of resources (i.e. water and energy) and biomass/waste generation. There has been much research work done to address resource conservation and sustainability issues in PPMs. An integrated pulp and paper biorefinery (IPPB) provides a means for the generation of higher value added product from biomass. Essentially, an IPPB acts as an EIP, where the enterprises (i.e. PPM, biorefinery and other potential enterprises) attempt to collaborate to achieve collective material, energy, economic and environmental benefits.

However, in a given EIP initiative, competition would arise among the participating enterprises. This could be attributed to the individual self-interests of the enterprises, where each seeks to maximize their individual payoff over the collective payoff of the EIP. Often, each enterprise has its own preference towards the optimal EIP scheme, subjected to criteria such as individual economic and environmental payoff. Consequently, this gives rise to a multiple criteria decision making (MCDM) problem. As such, there would be disagreement among the enterprises on the optimal EIP scheme to be implemented.

Currently, there is limited work done on developing a systematic approach to address the sustainability and strategic decision making (SDM) problem of an IPPB. A SDM framework allows for the design of an IPPB across multiple criteria and multiple decision makers. Concurrently, it is essential that the synthesized IPPB adheres to the fair distribution of economic and environmental payoff among the enterprises.

1.3. Research Objectives

The objectives of this research project are:

1. To synthesize resource conservation networks in an IPPB using mathematical optimization techniques.

   An optimization model is formulated, which is capable of integrating the material (i.e. water), energy and waste (i.e. biomass) flow in an IPPB. Concurrently, the model would synthesize an optimal biomass conversion pathway. Here, different biomass conversion pathways are considered. This includes direct combustion or gasification of biomass for the generation of biofuel and bioenergy.

2. To synthesize a sustainable EIP using mathematical optimization techniques with simultaneous consideration of both economic and environmental performance.

   An optimization model is formulated which uses an index, termed *eco-connectance* (C^{E}) to quantify the environmental performance of an IPPB case study (i.e. EIP). C^{E} relates the number of actual linkages over the maximum number of potential linkages in an EIP. The index is embedded into the optimization model with the economic performance (i.e. payback period) of an EIP to report a global optimum solution.

3. To develop a strategic decision making (SDM) framework to resolve the inherent competition present among enterprises.

   A systematic SDM framework using three different game models is applied, which are non-cooperative game, cooperative game and Stackelberg game. Each game model considers the preference of each enterprise in the EIP with respect to both economic and environmental payoff. An optimal EIP scheme, which is agreeable to all enterprises, is determined, subjected to fair distribution of both payoffs.

4. To incorporate the SDM framework with mathematical optimization techniques.

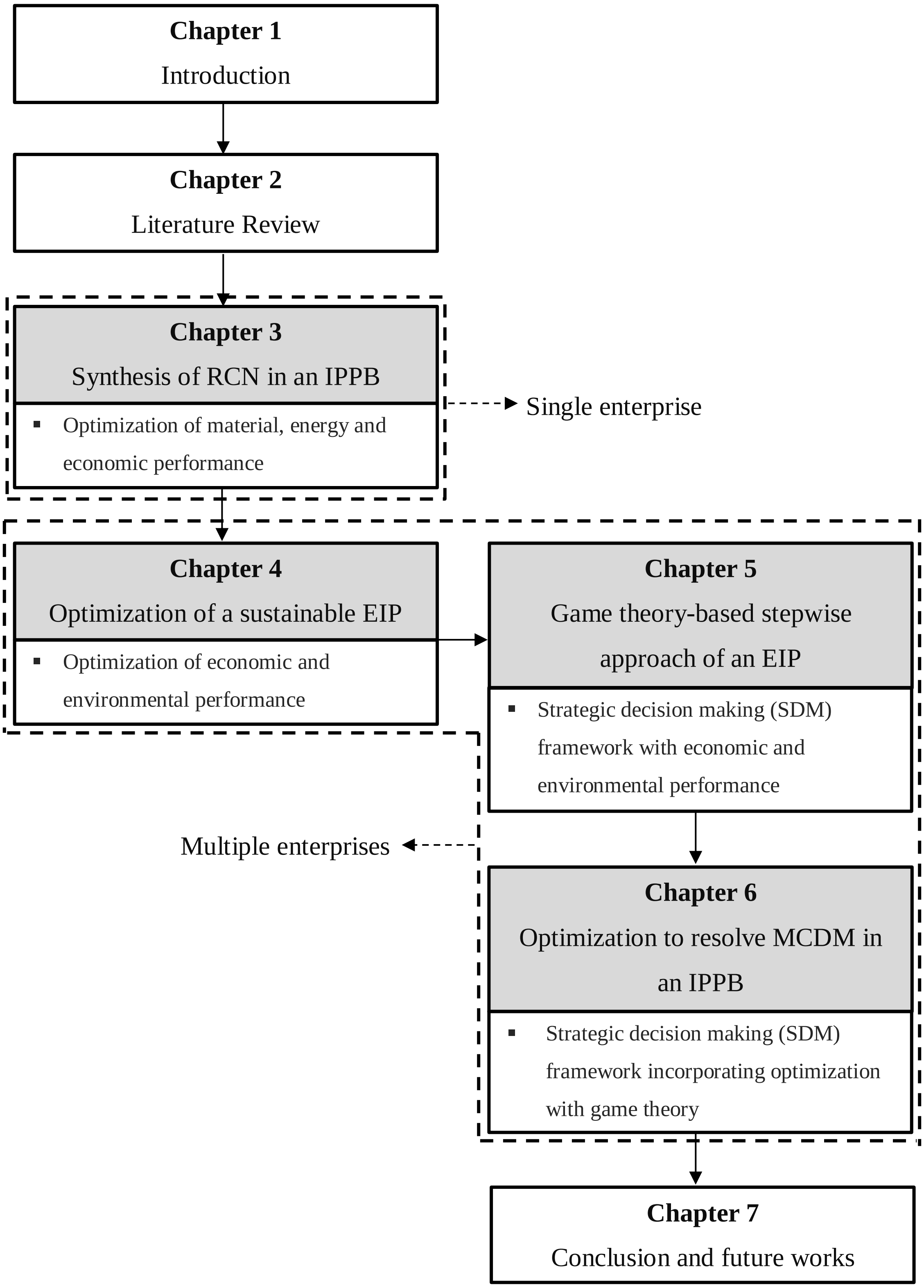
   An optimization model is formulated for an IPPB, which reports a global optimum solution. Cooperative game model is then applied to distribute the profits and costs among enterprises.

1.4. Research Scopes

The research project primarily deals with the synthesis of a sustainable integrated pulp and paper biorefinery (IPPB) subjected to strategic decision making (SDM). In **Chapter 3**, a systematic approach for the synthesis of resource conservation networks in an IPPB is developed. As noted earlier, an IPPB represents a complex processing facility where a PPM incorporates the biorefinery process to improve its market portfolio and viability. In this stage, a mathematical model is formulated which accounts for the simultaneous consideration of water and energy consumption of an IPPB. An optimal solution is to be reported, where the resource (water and energy) consumption of PPM is to be minimized without compromising the processing capability of the biorefinery. The model is to report an optimal IPPB scheme which maximizes profitability. Next, the environmental performance of the EIP is addressed in **Chapter 4**. In this stage, eco-connectance (C^E) is used as an environmental indicator. It quantifies the level of industrial symbiosis linkages in the EIP. A mathematical model is formulated which maximizes C^E subjected to economic constraints. An optimal EIP scheme is to be generated by the model with the optimal industrial symbiosis linkages and positive economic performance.

Next, in **Chapter 5 and 6**, the synthesis of a sustainable IPPB with strategic decision making (SDM) is addressed. This is achieved using multiple criteria decision making (MCDM) tools such as game theory. In **Chapter 5**, game theory is used to resolve the inherent competition among participating enterprises in an EIP. Often, individual enterprises would prioritize their self-interest in any decision making over the collective interest of an EIP, Hence, this results in differing preference by each enterprise on the optimal EIP scheme. Game theory is a mathematical study of cooperation and competition between rational decision-makers. Here, three game models are adopted to achieve an optimal EIP scheme. A systematic stepwise approach is proposed for each game model, with the ultimate aim of resolving the conflict present when multiple decision makers are involved in the EIP initiative. Through game theory, an optimal EIP network is reported which satisfies the economic and environmental performance of each participating enterprise. Concurrently, it is paramount that a fair distribution of economic and environmental payoff is achieved, to ensure EIP stability. Lastly, in **Chapter 6**, an optimization model is formulated to report a global optimum EIP, with respect to its overall economic payoff. The optimum solution is then analysed through cooperative game model.

1.5. Research Strategy



1.6. Research Contribution

The contribution of the research project is to synthesize a sustainable integrated pulp and paper biorefinery (IPPB) subjected to a strategic decision making (SDM) framework. The proposed IPPB operates as an EIP, which is comprised of multiple enterprises. A mathematical model is formulated for an IPPB using LINGO optimization software. The model optimizes for material, energy, waste (i.e. biomass), economic and environmental factors in an IPPB. Here, economic performance uses profitability while eco-connectance and CO_2 emissions are used to quantify the environmental performance of an IPPB. The optimization model formulated reported a global optimum solution for all IPPB case studies. The formulated model can be used to effectively screen for the most techno-economic feasible biorefinery pathways. Given the emergence of biorefineries as a viable alternative business practice for pulp and paper mills, the formulated mathematical model would inevitably be a useful tool during the decision making process.

In addition, a SDM framework is also developed which aids in resolving multiple-criteria decision making (MCDM) during the planning of an EIP project. The resulting research outcome can serve as a preliminary design and decision making tool to aid the pulp and paper industry. Besides, the formulated model and framework is generic to be adapted to other EIPs to achieve their respective sustainability goals (i.e. economics and environmental performances). Furthermore, the SDM framework would assist in providing insights into the system behaviour of an EIP. This is of particular importance as it would aid the EIP authority (i.e. governmental body) in future policy planning and EIP implementation. Finally, the use of both mathematical optimization and game theoretic approach as part of the SDM framework is capable of creating both sustainable and reconcilable solution among multiple enterprises in the EIP.

Chapter 2: Literature Review

2.1. Process Systems Engineering

The use of process systems engineering (PSE) techniques provides a systematic approach to address the issues of sustainability in an EIP. PSE encompasses the field of process integration, which can be defined as the "*holistic approach to process design, retrofitting and operation which emphasizes the unity of the process*" [21]. Essentially, process integration studies a given process in its entirety, with consideration to the interactions between process units, resources and streams, allowing for improved material and energy recovery. This is analogous when studying EIPs, where the interactions of multiple enterprises are considered as a whole, as opposed to studying a single enterprise. Research work conducted on process integration can be broadly classified based on insight-based *pinch analysis* and *mathematical optimization* techniques.

There has been numerous works addressing the synthesis of resource conservation networks (RCNs) using process systems engineering (PSE) techniques [22-28]. Kokossis and Yang (2010) concluded that the use of PSE techniques can greatly assist in the synthesis of integrated biorefineries [29]. Besides, mathematical optimization techniques had also been used to address for resource conservation in the palm oil industry by Ng *et al.* (2013) and an EIP by Aviso *et al.* (2010) [30, 31]. Next, fuzzy optimization had been documented to optimize an EIP under water footprint constraints and in a waste-to-energy EIP [13, 32]. On the other hand, Ng *et al.* (2015) adopted stability analysis with an mathematical model for the optimal planning and synthesis of an energy-based EIP [33]. From the literature above, it is seen that PSE techniques provide a powerful tool towards addressing sustainability through the synthesis of RCNs. Thus, it is the purpose of this research project to use mathematical optimization technique to synthesize a sustainable IPPB with strategic decision making (SDM).

2.2. Resource Conservation in Pulp and Paper Mills

Process integration has been widely used in pulp and paper mills, both through conventional *pinch analysis* and *mathematical optimization* techniques. The majority of research works have focused on the minimization of water and energy consumption. For instance, *pinch analysis* has been used to study on the optimization of water consumption and heat consumption [34, 35]. Besides, there have also been reported works that address simultaneous water and energy savings [36-43]. Here, various process changes have been studied from the synthesis of heat exchanger networks to the effect of process stream mixing and the segregation wastewater streams. In summary, it was found that water and energy consumption in pulp and paper mills are highly interactive, where the reduction in one of these resources can lead to savings in the other.

Aside from pinch analysis, *mathematical optimization* techniques have also been developed to address resource conservation problems in pulp and paper mills. In water network synthesis, Linear Programming (LP) model has been studied [34, 44]. Besides, mathematical model had also been reported for energy optimization in pulp and paper mills [45-47]. More recently, Chew *et al.* (2013) presented a Mixed-Integer Non-Linear Programming (MINLP) model for the simultaneous optimization of water and energy consumption [48]. Note that the literature reviewed above focuses only on the optimization of water and energy in pulp and paper mills (PPMs). However, recent development in integrated biorefineries present another opportunity for material and energy recovery in PPMs. An integrated pulp and paper biorefinery (IPPB) allows for increased marketability through the generation of bio-products and bioenergy from pulp and paper mill biomass. There has been much research work looking into the techno-economic feasibility of integrated biorefineries. Given the complexity of such a large industrial cluster, there would be significant interaction in its material and energy flow. Although there have been experimental and simulation works done on an IPPB, the simultaneous integration of water, energy and biomass has not yet been fully explored. This serves as the motivation of study in **Chapter 3**, which proposes a systematic approach for the synthesis of resource conservation networks in an IPPB. The proposed work examines opportunity for further water and energy savings in an IPPB by formulating an optimization model which selects the most profitable biorefinery pathway. A literature on biorefinery processes and the various biomass conversion pathways is presented next in **Section 2.3**.

2.3. Biorefinery and Biomass Conversion Technologies

The energy shortage crisis in the 1970s saw the initial transition from non-renewable carbon resources to renewable bioresources [49]. Biofuel is referred to as any solid, liquid or gaseous fuels that are produced primarily from biorenewable feedstocks [50]. Biofuel technology emerged as a potential solution to cater for rising energy demand as a result of population growth and environmental degradation. The attraction of biomass conversion technology lies in the ability to satisfy human needs for energy while simultaneously mitigating GHG emission mitigation that normally plagues conventional fossil fuel and coal usage.

Biofuel production is achieved through the processing of biomass feedstocks derived from either crops, forest and agricultural residues, industrial waste or algae [51]. Biofuels are generally classified based on their production technologies, namely first generation biofuels, second generation biofuels and third generation biofuels. **Table 2.1**, adapted from Demirbas (2009) depicts the classification of biofuels based on their production technologies [50]. First generation biofuels derive their feedstock mostly from food crops such as corn, grains and sugar. However, due to their limited ability to effectively substitute conventional fossil fuels along with the tendency to compete with food sources, first generation biofuels has saw declining interest. Next, development trend then focused on second generation biofuels which are produced from lignocellulosic materials such as forest and agricultural residues, wheat straw and municipal solid waste [52]. Lastly, third generation biofuel is biofuel produced from algae. Second and third generation biofuels are referred to as advanced biofuels.

Table 2.1. Classification of renewable biofuels based on their production technologies [50]

Generation	Feedstock	Biofuel Example
First generation biofuels	Sugar, starch, vegetable oils, or animal fats	Bioalcohols, vegetable oil, biodiesel, biosyngas, biogas
Second generation biofuels	Non-food crops, wheat straw, corn, wood, solid waste, energy crop	Bioalcohols, bio-oil, bio-DMF, biohydrogen, bio-Fischer-Tropsch diesel, wood diesel
Third generation biofuels	Algae	Vegetable oil, biodiesel

Biorefinery is a processing facility that receives biomass feedstocks and produces several chemicals (including biofuels) through a system of physical/chemical/biological processes (**Figure 2.1**) [53]. Biorefinery functions similar to conventional petrochemical refinery, capable of producing high-value low-volume output and low-value high-volume outputs [54]. Depending on the geographical location of biorefinery, products can be adapted to suit the local economic needs, be it low value transportation biofuels or high value added specialty chemicals and commodities for export purposes.

Kamm *et al.* (2004) were one of earliest authors to review the underlying principle in biorefineries [55]. Initial development of biorefineries was restricted to single biomass feedstock and fixed processing capabilities. However, recent development saw the emergence of an integrated biorefinery, capable of handling multiple biomass feedstocks and yield an array of bio-products through a combination of conversion technologies. The integrated biorefinery is fully capable of handling multiple bio-resources (plant derivatives or other solid waste) into a plethora of biomaterials, biofuel and bioenergy. Biorefineries utilizing second generation biomass are building on the foundation laid by previous generation to increase product range, driving for higher value-added commodities. Various bioprocessing technologies from pyrolysis, gasification, Fischer-Tropsch synthesis to catalytic reactions are being developed and refined to achieve the set goals.

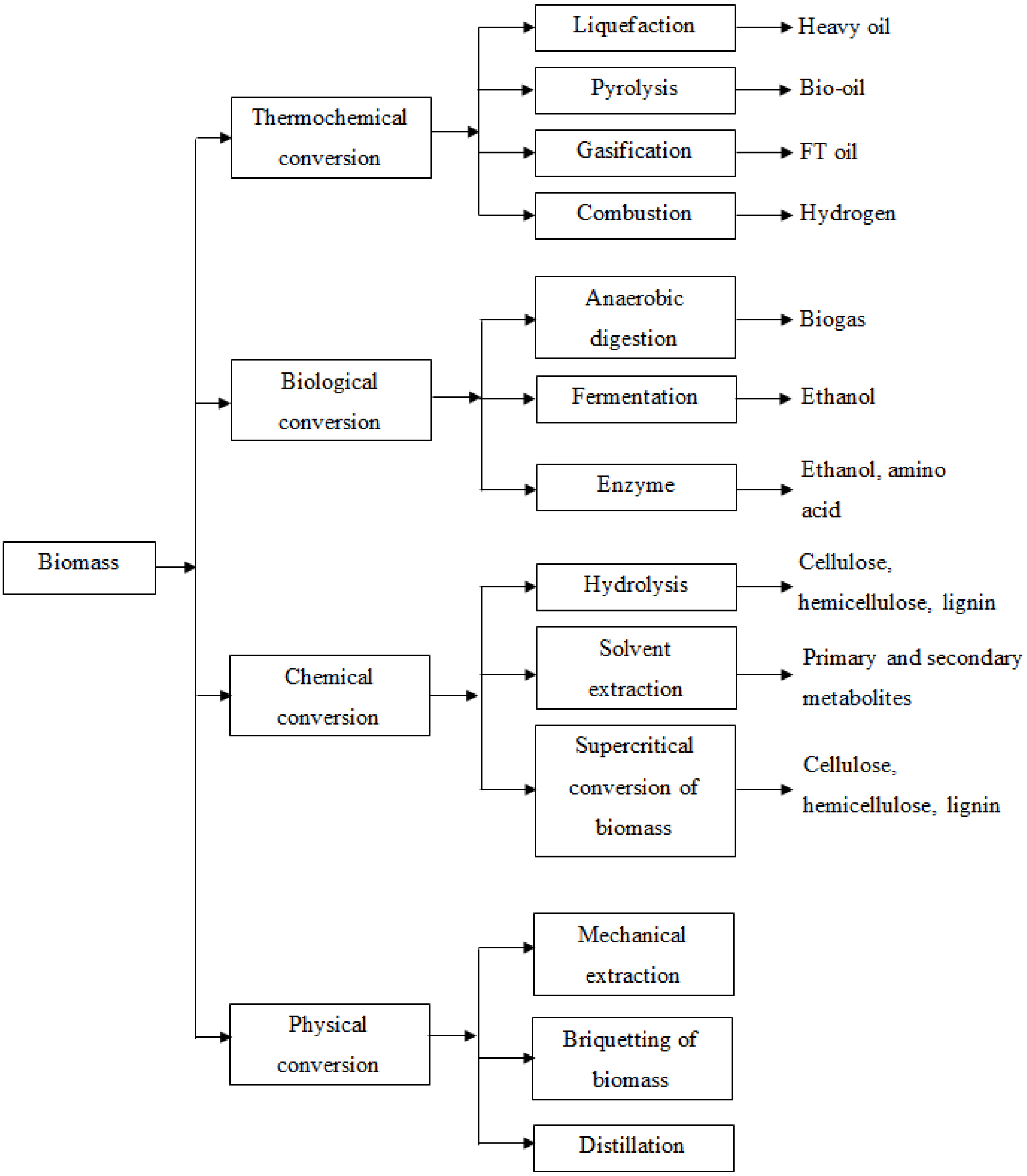


Figure 2.1. Biomass conversion processes [51]

The integrated biorefinery handles a variety of biomass feedstock either through *biochemical* or *thermochemical* pathway. The biochemical processing of biomass can be achieved by fermentation, anaerobic digestion and transesterification. These pathways utilize biological and chemical processes to extract cellulose and hemicellulose in biomass into alcohols. On the other hand, thermochemical processing includes direct combustion, gasification and pyrolysis. As its name implies, this pathway utilizes thermal treatment (i.e. heat) to convert biomass into biofuel and bioenergy. Direct combustion is the most commonly used technology by burning biomass in an oxygen-rich environment to produce heat and power [51, 56]. Gasification however, involves the processing of biomass at high temperature with low oxygen levels to produce syngas [50, 56]. On the other hand, pyrolysis operates at the absence of oxygen to produce bio-oil and solid charcoal [51, 56]. There has been reported works on the synthesis of an integrated biorefinery through automated targeting [57, 58], C-H-O ternary diagram [59], and fuzzy optimization [19]. Azapagic (2014) also emphasized the importance of taking sustainability into consideration towards the synthesis of an integrated biorefinery [60].

2.4. Strategic Decision Making in Eco-Industrial Parks

Given the scale of operation in an IPPB, it is not uncommon for such a large industrial cluster to be operated by multiple independent enterprises. In fact, literature has reported biofuel production in PPMs at a much larger scale in Sweden [61]. Thus, the IPPB then operates essentially as an eco-industrial park (EIP), governed by multiple enterprises who seek to liaise together to improve resource savings and waste minimization. In an EIP, each enterprise yields equal power in the decision making process. Thus, as each enterprise has their own interests and goals, this gives rise to a multiple criteria decision making (MCDM) problem. Here, conflict arises as the individual interests of enterprises may not be aligned to achieve a mutually agreeable outcome. Consequently, there has been literature which highlighted the failure in the implementation of EIP, directly because the MCDM issue was poorly addressed [62, 63]. In light of this, there is a need for a strategic decision making (SDM) framework which accounts for the interests and goals of each enterprise. Concurrently, it is paramount that the sustainability goals of an EIP is achieved.

There has been various approaches developed in the literature to deal with the MCDM problems. For instance quantitative based approach include fuzzy optimization while attempt to address the qualitative nature of MCDM has seen the use of approaches such as fuzzy analytic hierarchy process (FAHP) and game theory. In fuzzy optimization, a variable, known as the degree of satisfaction (λ), is introduced [64, 65]. The satisfaction level is firstly defined and then bounded by fuzzy logic constraints. This is to ensure the individual goals of the enterprise are attained upon running the optimization model. Fuzzy optimization has been adopted to optimize for EIP under water footprint constraints, resource constraints and changes in process operability [32, 66, 67].

Moving on, *game theory* is yet another approach that could be used to resolve MCDM. It is the mathematical study of cooperation and competition among rational and intelligent decision-makers. Here, a game is defined as any interaction between two or more players (decision makers) who make decisions that will influence each other's outcome [68, 69]. Game theory has been developed extensively as a tool to analyse situations of interactive decision making, especially businesses [70, 71]. Later, research work to adopt game in EIP has focused on inter-plant water integration [72, 73], heat integration [74] and industrial ecosystems [75]. Besides, a simple linear programming model has also been developed to solve for cooperative games [76]. Although the literature reviewed above has look into the MCDM problem in EIP as a whole, there has not been significant work done to generate a SDM framework for an IPPB. In this research work, it is desired to utilize both mathematical optimization and different game models as a SDM framework to resolve MCDM problem in an IPPB.

Chapter 3: Synthesis of Resource Conservation Networks in an Integrated Pulp and Paper Biorefinery

3.1. Summary

Pulp and paper production consumes large amount of water and steam. In particular, water is used in brown stock washing system (BSWS) to separate spent white liquor from the pulp stream. The wastewater stream generated from BSWS, known as black liquor is a potential biomass. In the current practice, black liquor is concentrated and burnt in a recovery boiler to produce steam and electricity. However, recent development in an integrated biorefinery offers increased marketability in pulp and paper mills through the generation of both bio-products and bioenergy. It is common practice for steam generated from the combustion of black liquor to be integrated with pulp and paper mill to satisfy its heating demands. Note that the water consumption in BSWS directly affects the quantity and quality of black liquor. This will later affect the potential for steam generation and integration in pulp and paper mill. Thus, in this work, water and heat integration is performed for a pulp and paper mill with biorefinery. An integrated pulp and paper biorefinery (IPPB) is proposed which accounts for different conversion pathways of pulp and paper mill biomass. Apart from combustion, several gasification pathways are considered. A non-linear program (NLP) is formulated to synthesize an optimum IPPB with maximum resources conservation. Sensitivity analysis is then carried out based on the most significant parameters to analyze the robustness of the proposed IPPB.

3.2. Introduction

Industrial sector accounts for 20% of global freshwater consumption, with pulp and paper mills being one of the most resource intensive sectors [77]. Freshwater is commonly used in pulp and paper mills for pulp washing, paper forming and steam generation. Besides, the mills also consume high amount of steam during the cooking and evaporation processes [16, 17]. Therefore, sustainable resource management has been the main agenda in pulp and paper mills [78, 79]. **Figure 3.1** depicts a simplified pulp and paper mill production, highlighting the primary material and energy flow [44]. Firstly, wood chips are fed into the digester to produce pulp. In the digester, alkaline solution also known as white liquor is added to remove lignin in the wood chips. Next, the pulp is washed in brown stock washing systems (BSWS) where most of the spent white liquor is separated from the pulp stream to form weak black liquor (WBL). The WBL is then concentrated in a multiple-effect evaporator (MEE) to remove 65-80% of its water content. Later, the concentrated strong black liquor (SBL) with 20-35% moisture content is burnt in a recovery boiler to generate steam and power. On the other hand, the smelt produced from the recovery boiler is sent for liquor recovery. Here, white liquor is recovered from the smelt and recycled back to the cooking process. Meanwhile, the washed pulp from BSWS is sent to bleaching process for paper production.

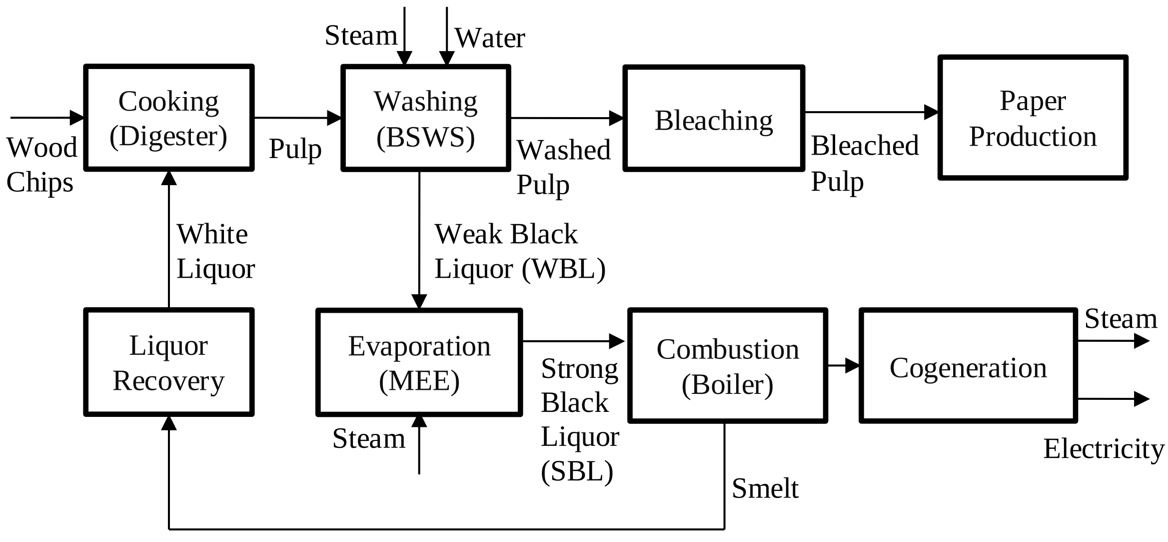


Figure 3.1. Simplified material and energy flow diagram for pulp and paper production

Viewing the need for sustainable management of resources in pulp and paper mills, *pinch analysis* and *mathematical optimization* techniques have been developed to minimize water and energy consumption. Koufos *et al.* (2001) used pinch analysis to determine the amount of heat recovery and water reuse in pulp and paper mills [36]. Note that the work by Koufus *et al.* address energy and water integration separately. Next, García *et al.* (2009) adopted pinch analysis to analyze the potential for energy savings on a Kraft mill [35]. Their work designed heat exchanger networks based on the classical *pinch design method* [80, 81]. Besides, much research works addressed simultaneous water and energy consumptions in pulp and paper mills through pinch analysis [37-40, 42]. Wising *et al.* (2005) studied the interaction between water consumption and the resulting potential for energy integration based on pinch analysis [37]. The authors reported that a reduction in water consumption led to improved heat recovery, allowing for a reduction in process steam demand. Next, Savulescu *et al.* (2005) identified a number of opportunities for heat recovery and wastewater reduction through pinch analysis [38]. These include projects such as increasing condensate return to boilers and segregating wastewater streams based on difference in temperature. Meanwhile, Alva-Argáez *et al.* (2009) presented a decision support system which studies the interaction between water and energy in pulp and paper mills [40]. Based on the proposed system, the optimum configuration of water distribution and heat exchanger networks can be identified. Savulescu and Alva-Argaez (2008) proposed a process integration methodology which address the impact of stream mixing on the overall energy efficiency of a pulp and paper mill [39]. Here, stream mixing occurs either between two process streams, during dilution of pulp with water or mixing of process stream with utility stream. Besides, Mateos-Espejel *et al.* (2010) studied the energy efficiency in pulp and paper mills by analyzing the interactions of different improvement techniques such as water reutilization and condensate recovery [42].

Apart from pinch analysis, mathematical optimization approaches are also developed to address resource conservation problems in pulp and paper mill. For example, Lovelady *et al.* (2008) presented a Linear Programming model to optimize water network system in the pulp mill while taking into consideration the build-up of Non-Process Elements (NPE) [44]. Ji *et al.* (2010) developed a model based on Mixed-Integer Linear Programming (MILP) to minimize cost via energy optimization in pulp and paper mill [46]. Besides, Marshman *et al.* (2010) presented a generic optimization model for pulp and paper mill cogeneration system, capable of accounting for varying factors such as different pulp and paper mills configurations and fuel purchases [47]. On the other hand, Chew *et al.* (2013) presented a Mixed-Integer Non-Linear Programming (MINLP) model to optimize water and energy consumption of brown stock washing system (BSWS) [48]. As shown in Chew *et al.* (2013), substantial savings in water and energy can be achieved through optimal reuse of water.

The development of an integrated biorefinery presents another opportunity for further energy recovery in pulp and paper mills. An integrated biorefinery is a sustainable processing facility which converts biomass into value added products such as biofuel and bioenergy [18, 19]. In pulp and paper mills, there are a number of potential biomass available. These include black liquor, wood residues, wastewater and sludge [20]. Generally, the development of biomass conversion technology had established into *biochemical* and *thermochemical* conversion pathways [29]. The former utilizes biological and chemical processes to extract cellulose and hemicellulose in biomass to convert into bio-products. Fermentation and anaerobic digestion are the typical examples of biochemical pathways. In fermentation, biomass pre-treatment is often necessary to make cellulose accessible for bioethanol production [82]. Biomass derived from agricultural residue such as wheat straw [83] and waste fibre sludge [84, 85] from pulp and paper mills has also been studied for bioethanol production. Meanwhile, pulp and paper mill wastewater and sludge treatment are used to produce biogas via anaerobic digestion [86]. On the other hand, thermochemical conversion technology which includes direct combustion, gasification and pyrolysis utilize thermal treatment to process biomass. Direct combustion is the most commonly used technology by burning biomass in an oxygen-rich environment to produce heat and power [51, 56]. Gasification however involves the processing of biomass at high temperature with low oxygen levels to produce syngas [50, 56]. On the other hand, pyrolysis operates at the absence of oxygen to produce bio-oil and solid charcoal [51, 56].

In pulp and paper mills, black liquor consists of residual inorganic chemicals and organic substances from the cooking process [87]. Black liquor is the most important biomass source, as it has high heating value, in the range of 13,000 – 15,500 kJ/kg [20]. According to Fatih (2009), direct combustion has been the most commonly used method in treating black liquor [50]. However, gasification allows for higher flexibility in its processes through the production of both bio-products and bioenergy [87, 88]. Thus, the development of black liquor gasification (BLG) has emerged as an attractive option to replace aging recovery boiler. Naqvi *et al.* (2010) provided an extensive review of recent developments in various BLG technologies [89]. The authors concluded that BLG provides an alternative for the replacement of recovery boiler to increase the profitability and energy efficiency of the industry. As shown in the literature, numerous works have been reported to establish an integrated biorefinery in pulp and paper mill using BLG [89-91]. Larson *et al.* (2008) assessed the commercial viability of black liquor and woody biomass gasification in a pulp and paper biorefinery [91]. As shown in Larson *et al.* (2008), detailed cost analysis on seven potential biorefinery design using gasification pathway were analysed. Later, Sammons *et al.* (2007) presented a systematic framework that evaluates the different biorefinery designs [92]. The work considered the economic performance based on net present value of biorefinery design while simultaneously addressing environmental impact. Subsequently, Tay *et al.* (2011) adapted fuzzy optimization to simultaneously optimize the allocation of biomass with consideration of both economic performance and environmental impact [19]. Next, a recent study by Fornell *et al.* (2013) concluded the technical and economic potential for combined ethanol and dimethyl ether production in pulp mills [93]. In the study, instead of paper production, pulp is sent for fermentation while black liquor generated is sent to gasification. Thus, it is seen that the incorporation of biorefinery using BLG can significantly improve the marketability of pulp and paper mills. More recently, Dansereau *et al.* (2014) presented an optimization model which address supply chain planning when implementing biorefinery in pulp and paper mills [94]. The work determines the profitability of the pulp and paper industry subjected to volatile market conditions. Azapagic (2014) also emphasized the importance of taking sustainability into consideration towards the synthesis of an integrated biorefinery [60].

On the other hand, there has also been research conducted on the potential for carbon capture and storage (CCS) from BLG [95]. Pettersson and Harvey (2010) studied the emission of CO_2 when introducing BLG in pulp and paper mills [96]. The authors evaluated CO_2 emissions of different biorefinery products (e.g. dimethyl ether (DME), methanol, FT-diesel (FTD) and electricity) and concluded BLG offers the potential for a reduction in CO_2 emissions. Later, Pettersson and Harvey (2012) compared BLG with conventional recovery boiler-based pulping process using both economic performance and the CO_2 emissions [95]. Two options for BLG were studied, black liquor gasification combined cycle (BLGCC) for electricity production and black liquor gasification with motor fuel production (BLGMF). BLGMF, producing DME was found to provide the better economic outcome compared with BLGCC. In addition, Joelsson and Gustavsson (2012) compared the potential for greenhouse gas emissions reductions between black liquor gasification with dimethyl ether production (BLG-DME) and black liquor gasification with Fischer-Tropsch fuel production (BLG-FT) in pulp mills [97]. The authors found that the integration potential and the reduction in greenhouse gas emissions for BLG-DME is better than BLG-FT. Besides, Naqvi *et al.* (2012)

reported the possibility of CO_2 reduction using synthetic natural gas (SNG) from BLG to replace natural gas [98].

The aforementioned studies had indicated the potential technological and economic advantageous of an integrated biorefinery in pulp and paper mills over conventional Kraft pulping [88-92, 95]. Based on the previous works, it is noted that there is limited work which considers simultaneous water and energy integration in an integrated pulp and paper biorefinery (IPPB). An IPPB represents a complex processing facility which incorporates biorefinery into pulp and paper mill. The consideration of both water and energy integration is particularly crucial as the water consumption in BSWS directly affects the quantity and quality (i.e. moisture content) of black liquor. This will then affect the steam requirement during the evaporation process. Concurrently, the quantity and quality of black liquor produced directly affects the amount of bioenergy (or bioproducts) that can be generated in biorefinery. As a result, the overall energy efficiency of an IPPB is determined from the amount of steam that can be integrated with BSWS. The interaction between water and energy flow in BSWS with MEE and recovery boiler is depicted in **Figure 3.2**.

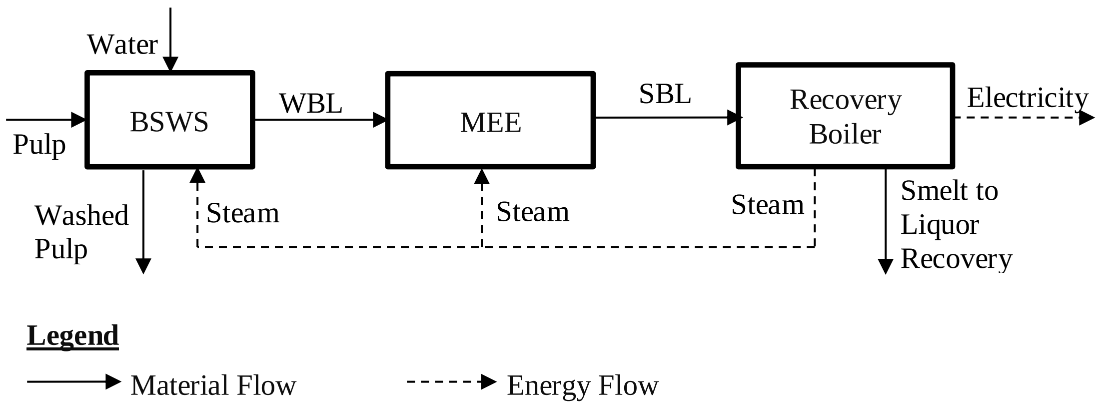


Figure 3.2. A schematic depicting steam interaction between BSWS with MEE and recovery boiler

The main aim of this work is to propose a systematic approach for the synthesis of resource conservation networks in an IPPB. A mathematical optimization model is developed which simultaneously considers the interaction of water and energy consumptions between pulp and paper mill with biorefinery. Concurrently, the model will account for the optimal generation of biofuel and bioenergy in an IPPB. Lastly, the systematic allocation of steam generated from an IPPB will also be determined (i.e. integrated with pulp and paper mill or sold as revenue). A case study is solved to illustrate the proposed approach.

3.3. Problem Statement

The problem definition for the synthesis of an IPPB can be stated as follow: Biomass $b \in B$ (e.g. black liquor and wood residues) produced from pulp and paper mill is sent to biorefinery processing pathway $k \in K$ (e.g. gasification and combustion). In biorefinery, intermediate product $l \in L$ (e.g. syngas and biogas) is produced from processing pathway $k \in K$ and later upgraded into final product $l' \in L'$ through processing pathway $k' \in K'$ (e.g. DME synthesis and FT synthesis). Note that the final products derived from the biorefinery may consist of biofuel, bioenergy (e.g. process steam, electrical power, etc.) and bio-products (e.g. methane, acid, biochar, etc.).

A superstructural representation of an IPPB is shown in **Figure 3.3** [57]. Given the various biorefinery pathways available for pulp and paper mills, **Figure 3.3** represents all the possible pathways mathematically. In this work, it is noted that biomass sent to an IPPB is limited to a single source. Black liquor generated from BSWS is taken as the biomass source due to its high heating value of black liquor [20]. It is desired to synthesize resource conservation networks through optimal allocation of water reuse in BSWS and steam integration between BSWS and the biorefinery. The objective function of the optimization model is set to determine the gross profit (GP) of implementing an IPPB. The GP will account for the investment cost (fixed and variable costs) of an IPPB. The following section details the proposed methodology used to formulate the mathematical model.

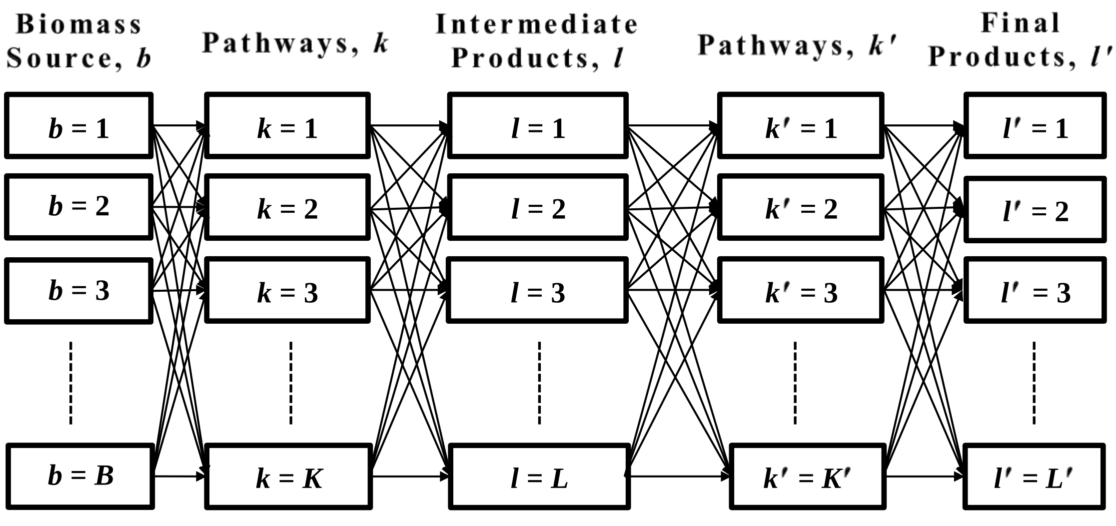


Figure 3.3. Superstructural representation of an integrated biorefinery [57]

3.4. Methodology for Model Formulation

3.4.1. Brown Stock Washing System (BSWS)

BSWS consists of a set of washers with fixed flow rates requirement and displacement ratio (DR) and is depicted in **Figure 3.4**. Variables CF_i^D, CF_i^S, CF_i^F and CF_i^P in **Figure 3.4** denote dissolved solids (DS) concentration at dilution, shower, filtrate and pulp outlet, respectively. DR expresses the effectiveness of a single displacement washing stage in removing DS in the pulp stream. It can be defined as the ratio of actual reduction of DS in a washing stage compared to the maximum possible DS reduction [48].

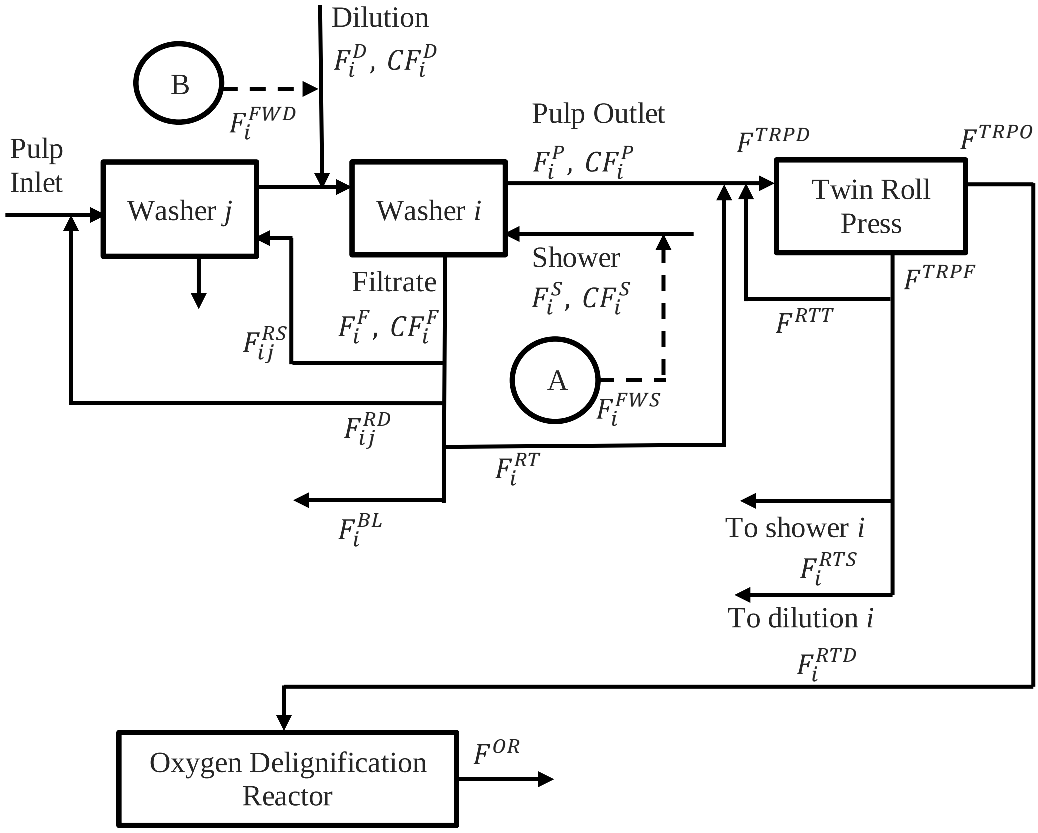


Figure 3.4. Schematic representation of a counter-current BSWS

Each washer consists of two inlet flow (dilution and shower point) and two outlet flow (filtrate and pulp outlet). The amount of water that can be reused from filtrate is constrained by both the washer efficiency (DR) and the final DS content of pulp stream leaving BSWS. Water sources refer to process streams where water can be reused and this is derived from the filtrate flow rate (F_i^F) of each of the washers. Next, water sinks refer to process streams which can accept reused/recycled water and this includes the shower flow rate (F_i^S) and dilution point flow rate (F_i^D). Locations A and B represent possible make up point for freshwater into shower and dilution point, respectively. It is desired to reuse/recycle water within the washers $i \in I$, with DS being the limiting constraint of the water recovery scheme. In the following sub-sections, mass and heat balances for BSWS are discussed.

3.4.1.1. Mass Balance of Washers

Mass balance across each of the washer is formulated as represented by Eq (3.1). Next, Eq (3.2) presents the DS balance across each washer *i*. Superscripts *D*, *S*, *P* and *F* represents dilution point, shower inlet, pulp and filtrate outlet of each washer *i*, respectively.

$$F_i^D + F_i^S = F_i^P + F_i^F \qquad \forall i \qquad (3.1)$$

$$F_i^D CF_i^D + F_i^S CF_i^S = F_i^P CF_i^P + F_i^F CF_i^F \qquad \forall i \qquad (3.2)$$

Eq (3.3) below presents the relationship between the washer's efficiency DR$_i$ with DS concentration [48].

$$\mathrm{DR}_i = \frac{(CF_i^D - CF_i^P)}{(CF_i^D - CF_i^S)} \qquad \forall i \qquad (3.3)$$

Note that the filtrate stream of each washer in BSWS can be reused in other washers or the twin roll press (see **Figure 3.4**). The twin roll press represents a unit operation responsible for the removal of excess water present in the pulp stream. Eq (3.4) describes the source flow rate balance (filtrate). The variable F_{ij}^{RS} denotes the reused filtrate flow rate of washer *i* to shower of another washer *j*. Similarly, F_{ij}^{RD} denotes the reused flow rate of water from filtrate of washer *i* to dilution of another washer *j*. The variable F_i^{RT} represents the filtrate flow rate from washer *i* being reused into the inlet of the twin roll press (TRP). Lastly, the excess filtrate flow rate will be discharged as weak black liquor (WBL), F_i^{BL}.

$$F_i^F = \sum_j F_{ij}^{RS} + \sum_j F_{ij}^{RD} + F_i^{RT} + F_i^{BL} \qquad \forall i, j \qquad (3.4)$$

Next, the formulations of water sinks are described below. Water sinks are capable of reusing water from the filtrate of washers and the filtrate outlet of the twin roll press. Freshwater is then supplied to satisfy any remaining water requirement of water sinks. Eqs (3.5) and (3.6) describe the total flow rate and DS balance for shower point of washer *i*, with F_i^{RTS} denoting the reused flow rate of TRP filtrate into the shower. The term F_i^{FWS} represents freshwater makeup at shower point. Next, the term CF_i^{RTS} represents DS concentration of TRP filtrate outlet being reused at shower point.

$$F_i^S = \sum_j F_{ij}^{RS} + F_i^{RTS} + F_i^{FWS} \quad \forall i,j \quad (3.5)$$

$$F_i^S CF_i^S = \sum_j (F_{ij}^{RS} CF_i^F) + F_i^{RTS} CF_i^{RTS} + F_i^{FWS} CF^{FW} \quad \forall i,j \quad (3.6)$$

Similarly, Eqs (3.7) and (3.8) describe the total flow rate and DS balance for dilution point of washer i, with F_i^{RTD} denoting the reused flow rate of TRP pressate into dilution point. The term F_{i-1}^P denotes the receiving pulp flow rate from the previous washer while F_i^{FWD} represents freshwater makeup flow rate at dilution point. Next, term CF_i^{RTD} represents DS concentration of TRP filtrate being reused at dilution point.

$$F_i^D = \sum_j F_{ij}^{RD} + F_i^{RTD} + F_{i-1}^P + F_i^{FWD} \quad \forall i,j \quad (3.7)$$

$$F_i^D CF_i^D = \sum_j (F_{ij}^{RD} CF_i^F) + F_i^{RTD} CF_i^{RTD} + F_{i-1}^P CF_{i-1}^P + F_i^{FWD} CF^{FW} \quad \forall i,j \quad (3.8)$$

Following this, the total freshwater requirements in BSWS (F^{FW}) is shown in Eq (3.9).

$$F^{FW} = \sum_i F_i^{FWS} + \sum_i F_i^{FWD} + F^{FWT} \quad (3.9)$$

where F_i^{FWS}, F_i^{FWD} and F^{FWT} are the freshwater flow rates for shower *i*, dilution *i* and twin roll press with a concentration of CF^{FW}.

Eq (3.10) represents total WBL flow rate generated (F_i^{BL}) where a portion is allowed to be recycled (F_i^{BLR}) back to the first washer; while other portion (F_i^{BLE}) is being sent to multiple-effect evaporator (MEE) for evaporation.

$$\sum_i F_i^{BL} = \sum_i F_i^{BLE} + \sum_i F_i^{BLR} \quad (3.10)$$

Eq (3.11) shows the mass balance of MEE, where the moisture content in WBL (F^V) is removed to produce strong black liquor (F^{SBL}). The SBL is then sent for thermochemical conversion for energy recovery or production of value added products.

$$\sum_i F_i^{BLE} = F^{SBL} + F^V \quad (3.11)$$

3.4.1.2. Mass Balance of Twin Roll Press

Twin roll press (TRP) serves to remove excess water present in the pulp stream during the washing process (see **Figure 3.4**). TRP is modeled as a water removal unit operation. Eq

(3.12) denotes the flow rate balance across TRP with F^{TRPD}, F^{TRPF} and F^{TRPO} representing flow rate at dilution point of TRP, filtrate outlet and pulp outlet stream, respectively.

$$F^{TRPD} = F^{TRPF} + F^{TRPO} \quad (3.12)$$

As shown in Eq (3.13) the inlet flow rate of TRP (F^{TRPD}) can receive reused water from washer filtrate and freshwater as well as self-recycle water (F^{RTT}). A DS balance across the water inlet of TRP is also formulated as shown in Eq (3.14).

$$F^{TRPD} = \sum_i F_i^{RT} + F^{RTT} + F_{i-1}^{P} + F^{FWT} \quad (3.13)$$

$$F^{TRPD} CF^{TRPD} = \sum_i (F_i^{RT} CF_i^{F}) + F^{RTT} CF^{TRPF} + F_{i-1}^{P} CF_{i-1}^{P} + F^{FWT} C^{FW} \quad (3.14)$$

Next, the outlet flow rate balance of TRP is shown in Eq (3.15), where it supplies water to shower (F_i^{RTS}) and dilution (F_i^{RTD}) of washers. In this work, it is assumed that the total DS content at dilution point of TRP (CF^{TRPD}), TRP filtrate (CF^{TRPF}) and TRP outlet (CF^{TRPO}) remains constant, as shown in Eq (3.16).The assumption is based on Chew *et al.* [48] which models the TRP as a unit operation which removes water from the pulp stream. Thus, only a change in water flow rate is observed while the DS concentration in the pulp stream is assumed to be fixed.

$$F^{TRPF} = \sum_i F_i^{RTS} + \sum_i F_i^{RTD} + F^{RTT} \quad (3.15)$$

$$CF^{TRPD} = CF^{TRPF} = CF^{TRPO} \quad (3.16)$$

3.4.1.3. Mass Balance of Oxygen Delignification Reactor

The oxygen delignification reactor is responsible for the further delignification of lignin present in the pulp stream (see **Figure 3.4**). A mathematical formulation for the oxygen delignification reactor is presented below. Eq (3.17) denotes the assumption that the pulp flow rate exiting the reactor (F^{OR}) remains constant, where F^{TRPO} denotes the flow rate leaving the TRP [48].

$$F^{OR} = F^{TRPO} \quad (3.17)$$

Next, the DS balance across the oxygen delignification reactor is formulated in Eq (3.18). The DS balance solves for the variable CF^{OR}, which denotes the DS concentration of the reactor exit stream. Variable F^{DSOR} denotes the increase in the amount of lignin after the delignification process. The value for F^{DSOR} can be determined depending on the case study being adapted [48].

$$F^{OR}CF^{OR} = F^{TRPO}\, CF^{TRPO} + F^{DSOR} \quad (3.18)$$

3.4.1.4. Heat Balances

The following section describes the formulation of heat requirements in BSWS. The main heating requirement of BSWS is identified as the evaporation process and the pre-heating in the oxygen delignification reactor. Process steam is supplied to the MEE to remove moisture from the WBL produced. The formulation for MEE is represented by Eq (3.19). It should be highlighted that the amount of energy required in MEE (Q^{MEE}) is related to the amount of black liquor generated ($\sum_i F_i^{BLE}$) in Eq (3.11). The variables $\overline{\mathrm{H}}$ and *a* denote the specific heat of water and efficiency of MEE, respectively.

$$Q^{MEE} = \frac{F^{V}\overline{\mathrm{H}}}{\mathrm{a}} \quad (3.19)$$

Eq (3.20) denotes the heat demand (Q^{OR}) in oxygen delignification reactor where the variable T^{TRP} represents the pulp stream temperature leaving the TRP. The variable $\mathrm{C_P^{OR}}$ denotes the heat capacity of pulp mat in reactor.

$$Q^{OR} = F^{TRPO}\mathrm{C_P^{OR}}(T^{OR} - T^{TRP}) \quad (3.20)$$

The total heat requirement in BSWS (Q^{TOT}) is the summation from multiple-effect evaporator, Q^{MEE} and oxygen delignification reactor, Q^{OR}, as shown in Eq (3.21).

$$Q^{TOT} = Q^{MEE} + Q^{OR} \quad (3.21)$$

Following this, energy balances are developed for the washers and are analogous to mass balance developed earlier. The variable *TF* represents stream temperature. Eq (3.22) presents energy balance across each washer; while, Eq (3.23) presents a constraint for the heat balances in terms of DR.

$$F_i^{D}TF_i^{D} + F_i^{S}TF_i^{S} = F_i^{P}TF_i^{P} + F_i^{F}TF_i^{F} \qquad \forall i \quad (3.22)$$

$$\mathrm{DR}_i = \frac{(TF_i^{D} - TF_i^{P})}{(TF_i^{D} - TF_i^{S})} \qquad \forall i \quad (3.23)$$

In Eq (3.24), the energy balance at shower point consists of process stream from filtrate (F_{ij}^{RS}) at temperature TF_i^{F} and from the twin roll press (F_i^{RTS}) at temperature TF_i^{RTS}. The term F_i^{FWS} represents freshwater makeup at shower point at temperature TF^{FW}.

$$F_i^{S}TF_i^{S} = \sum_j (F_{ij}^{RS}TF_i^{F}) + F_i^{RTS}TF_i^{RTS} + F_i^{FWS}TF^{FW} \qquad \forall i,j \quad (3.24)$$

Similarly, Eq (3.25) denotes the energy balance at dilution point, consisting of process stream from the filtrate filtrate (F_{ij}^{RD}) at temperature TF_i^F and from the twin roll press (F_i^{RTD}) at temperature TF_i^{RTS}. The dilution point also receive energy from the main pulp stream (F_{i-1}^P) at temperatureTF_{i-1}^P.

$$F_i^D TF_i^D = \sum_j (F_{ij}^{RD} TF_i^F) + F_i^{RTD} TF_i^{RTD} + F_{i-1}^P TF_{i-1}^P + F_i^{FWD} TF^{FW} \quad \forall i, j \qquad (3.25)$$

3.4.2. Thermal Conversion of Black Liquor

As shown in Eq (3.11), the SBL generated from MEE is then sent for thermal conversion in the biorefinery (see **Figure 3.6**). Eq (3.26) denotes the allocation of SBL to each of the possible biorefinery pathways k with flow rate F_k^{SBL}. Intermediate products l with flow rate F_l are generated at conversion factor of Y_{kl} via Eq (3.27).

$$F^{SBL} = \sum_k F_k^{SBL} \qquad (3.26)$$

$$F_l = \sum_k (\mathrm{Y}_{kl} F_k^{SBL}) \quad \forall l \qquad (3.27)$$

Next, intermediate products F_l are distributed to the next potential pathways k' each with an individual flow rate of $F_{lk'}^{INT}$ as shown in Eq (3.28). The final product with flow rate $F_{l'}^{PROD}$ is generated at conversion factor of $Y_{k'l'}$ as in Eq (3.29).

$$F_l = \sum_{k'} F_{lk'}^{INT} \quad \forall l \qquad (3.28)$$

$$F_{l'}^{PROD} = \sum_{l,k'} (\mathrm{Y}_{k'l'} F_{lk'}^{INT}) \quad \forall l' \qquad (3.29)$$

In addition, steam and electricity can be recovered from the biorefinery for each of the processing pathway. Eq (3.30) represents the amount of electrical power generated from pathway k and k' at conversion factors of Y_{ke}^{ELEC} and $Y_{k'e}^{ELEC}$respectively.

$$F_e^{ELEC} = \sum_k (\mathrm{Y}_{ke}^{\mathrm{ELEC}} F_k^{SBL}) + \sum_{l,k'} (\mathrm{Y}_{le}^{\mathrm{ELEC}} F_{lk'}^{INT}) \quad \forall e \qquad (3.30)$$

It is assumed that steam could be generated at two different levels; low pressure (LP) and medium pressure (MP) steam. Eqs (3.31) and (3.32) describe total LP and MP steam generated, respectively.

$$F_S^{LPST} = \sum_k (\mathrm{Y}_{ks}^{\mathrm{LPST}} F_k^{SBL}) + \sum_{l,k'} (\mathrm{Y}_{ls}^{\mathrm{LPST}} F_{lk'}^{INT}) \quad \forall s \qquad (3.31)$$

$$F_S^{MPST} = \sum_k (\mathrm{Y}_{kss}^{\mathrm{MPST}} F_k^{SBL}) + \sum_{l,k'} (\mathrm{Y}_{lss}^{\mathrm{MPST}} F_{lk'}^{INT}) \quad \forall s \qquad (3.32)$$

In this work, it is assumed that BSWS utilizes MP steam at 13 bar to satisfy its heating demand in MEE and the oxygen delignification reactor. Note that the operating pressure of MEE is given as 3.5 bar while oxygen delignification reactor operates at 10 bar.[99] Therefore, the available MP steam is sufficient to support both MEE and oxygen delignification reactor. To maximize the steam recovery, MP steam (F_S^{MPST}) generated from the biorefinery is supplied to BSWS ($F_S^{MPST\_BSWS}$) and the excess steam being sold for revenue ($F_S^{MPST\_EX}$), as indicated in Eq (3.33).

$$F_S^{MPST} = F_S^{MPST\_EX} + F_S^{MPST\_BSWS} \tag{3.33}$$

In addition, it is assumed that all generated LP steam (F_S^{LPST}) in the biorefinery can be sold to the nearby processing facilities as revenue. However, in the case where the MP steam from biorefinery is not self-sufficient for the BSWS, externally purchased steam ($F_S^{MPST\_PUR}$) is used to supplement the additional steam requirement ($F_S^{MPST\_REQ}$), as indicated in Eq (3.34).

$$F_S^{MPST\_REQ} = F_S^{MPST\_PUR} + F_S^{MPST\_BSWS} \tag{3.34}$$

3.4.3. Economic Analysis

The optimization objective is then set to maximize the economic performance of an integrated pulp and paper biorefinery.

$$\text{MAXIMIZE } GP = REVENUE - COST \tag{3.35}$$

where

$$REVENUE = [\sum_{l'} F_{l'}^{PROD} P_{l'}^{PROD} + \sum_e F_e^{ELEC} P_e^{ELEC} + \sum_s F_S^{MPST\_EX} P_S^{MP} + \sum_s F_S^{LPST} P_S^{LP}] \times \text{PR} \times \text{OH} \tag{3.36}$$

$$COST = [\sum_k \Upsilon_{kl} F_k^{SBL} P_{kl} + \sum_l \Upsilon_{k'l'} F_{lk'}^{INT} P_{k'l'} + F^{FW} P^{FW} + Q^{TOT} P^Q] \times \text{PR} \times \text{OH} \tag{3.37}$$

Note that all variables are expressed in dollars per year (USD/y). Gross profit (*GP*) is estimated based on the revenues (biofuels, steam and electricity) and costs/expenses spent in an integrated biorefinery (fixed and variable costs, water, and energy).

Referring to **Figure 3.3**, sets *k* and *k'* represents index for biomass conversion pathway while sets *l* and *l'* are the index for intermediate product and final product, respectively. Next, index *e* and *s* are electricity and steam, respectively. The variables $P_{l'}^{PROD}$, P_e^{ELEC}, P_S^{MP} and P_S^{LP}

represents selling price of the product, electricity and steam, respectively; while P_{kl}^{RM1} and $P_{k'l'}^{RM2}$ denote the processing cost of the biorefinery pathways. It is noted that the fixed and variable costs of each pathways are taken into consideration in the processing cost P_{kl}^{RM1} and $P_{k'l'}^{RM2}$. P^{FW} and P^{Q} are the cost of freshwater and energy consumption in BSWS, respectively.

3.5. Case Study

A BSWS base case study from Chew *et al.* (2013) [48] and a gasification-based biorefinery from Tay *et al.* (2011) [19] are solved to demonstrate the mathematical model. The BSWS consists of seven washers (i.e. EMCC, Diffuser 1, Diffuser 2, Decker Washer, Washer 1, Washer 2 and Washer 3) arranged in counter current mode as seen in **Figure 3.5**. **Table A1.1** in **Appendix 1** shows the washer flow rates and its respective DR. Note that the current freshwater consumption for the BSWS base case is at 12,321 kg/ton of pulp supplied to Decker Washer (2,891 kg/ton of pulp), Washer 1 (3,430 kg/ton of pulp) and Washer 3 (6,000 kg/ton of pulp). Meanwhile, the total steam consumption of BSWS (at the MEE and oxygen delignification reactor) is 2,420 kg/ton of pulp. WBL from washer filtrate that are not being reused are directed for evaporation in MEE. The produced SBL is then sent to the biorefinery for thermochemical conversion.

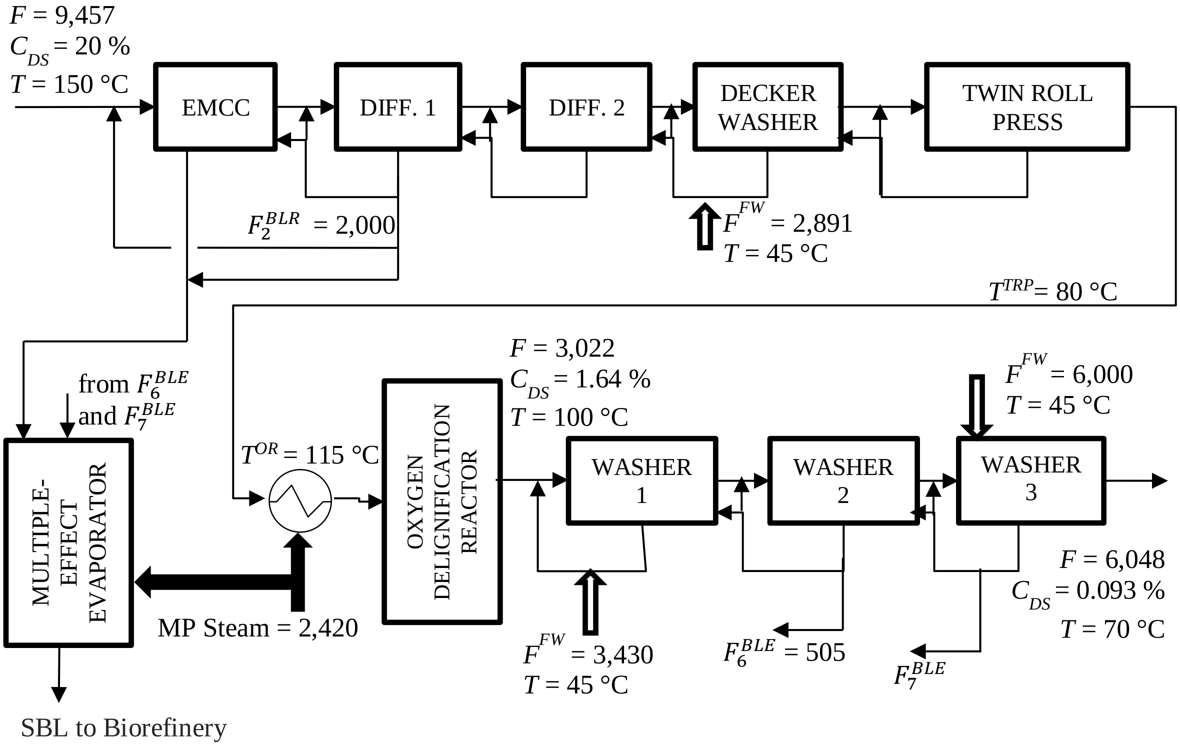


Figure 3.5. Base case process flow diagram of BSWS with MEE [48]
(All flow rates are in kg/ton of pulp unless reported otherwise)

In this case study, SBL can be sent either to a gasifier or recovery boiler. In the former pathway, syngas generated from the gasifier can either be used in a combined cycle turbine (BLGCC) to generate steam and electricity or for the production of dimethyl ether (DME), Fischer-Tropsch fuel (FT) and mixed alcohols (Mix-OH) as shown in **Figure 3.6** [100]. On the other hand, SBL may also be sent to a recovery boiler to generate process steam, which is later used to generate heat and power through cogeneration. Note that both combustion and gasification pathways allow for the generation of steam and power which can be integrated with BSWS.

Detailed information on the alternative biorefinery designs is shown in **Table 3.1**. For the DME process, three alternative configurations are identified denoted by DME^a, DME^b and DME^c, as studied and summarized by Larson *et al.* (2008) [91]. DME^a involves the production of DME as the main product utilizing BLG while producing steam and electricity as side products. In DME^b, an additional wood gasifier and gas turbine are utilized to produce additional syngas for steam and electricity generation. Any unconverted syngas in DME^a and DME^b is recycled back for DME synthesis. The DME^c process is similar to DME^b with the exception that in DME^{c}, any unconverted syngas is used to generate steam and electricity. On the other hand, three different alternatives for FT fuel production are also identified, denoted by FT^{a}, FT^{b} and FT^{c}. In FT^{a}, FT fuel is generated as the main product with the unconverted syngas being sent to a gas turbine for steam and electricity production. Next, FT^{b} employs a similar process as FT^{a} but uses a different type of gas turbine. In FT^{c}, FT fuel is generated from the syngas in wood gasification and black liquor gasification. Lastly, mixed alcohol synthesis pathway produces mixed alcohol from the syngas.

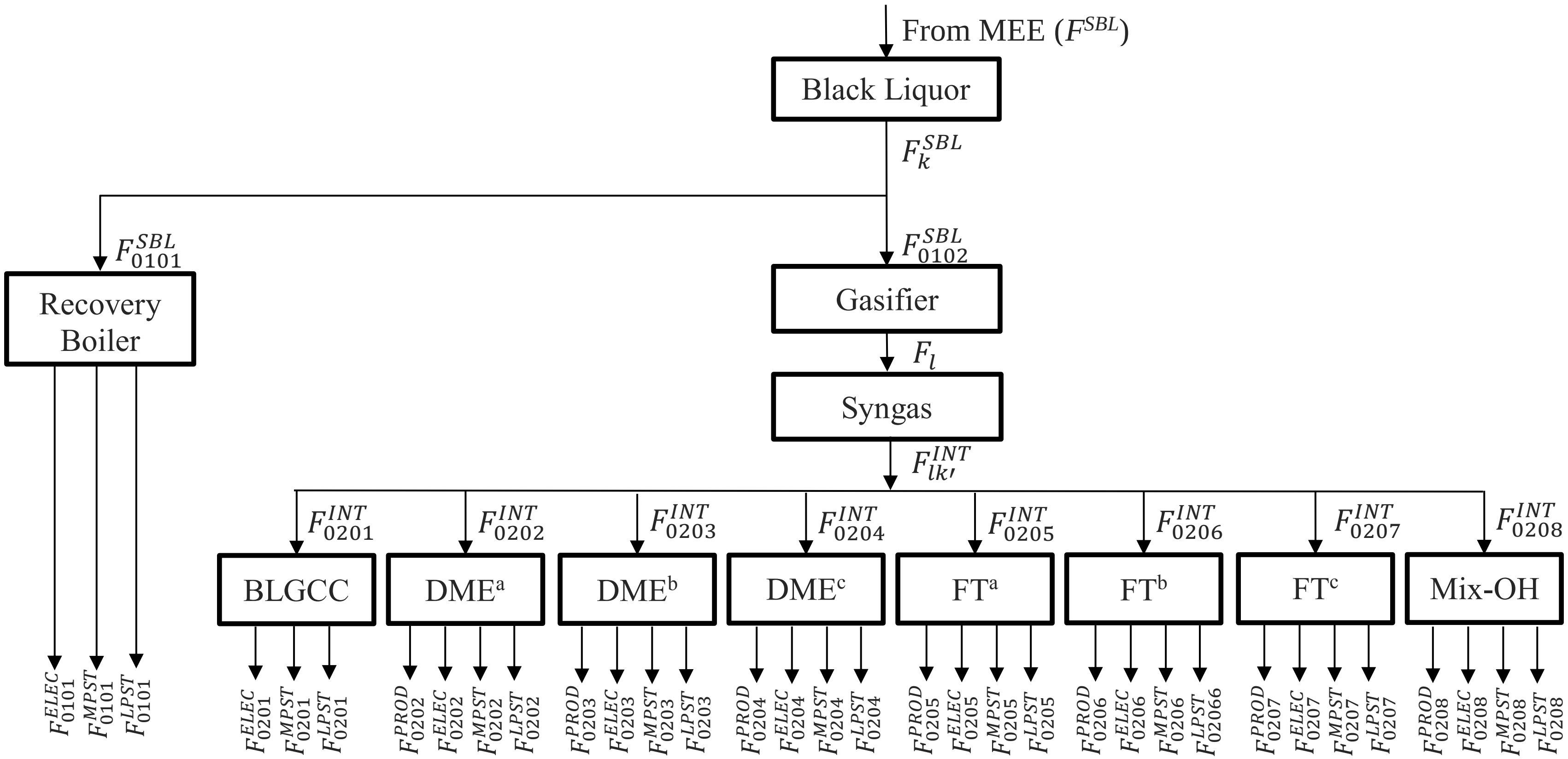


Figure 3.6. Alternative processing pathways for black liquor [19]

Table 3.1. Biorefinery designs pathway for existing pulp and paper industry [100]

Biorefinery designs	Product range	Description
Tomlinson boiler (TOM)	Electricity, steam	Base case, business as usual, replace aging Tomlinson boiler
Black liquor gasification, combined cycle (BLGCC)	Electricity, steam	Replace Tomlinson boiler with combined cycle turbine fired by syngas
Dimethyl ether, process A (DME^a)	Electricity (negligible), steam, dimethyl ether	No gas turbine, no wood gasification, 97% recycle of syngas from black liquor gasification through synthesis process
Dimethyl ether, process B (DME^b)	Electricity, steam, dimethyl ether	Wood gasification sent to gas turbine, 97% recycle of syngas
Dimethyl ether, process C (DME^c)	Electricity, steam, dimethyl ether	Wood gasification sent to gas turbine, one pass synthesis
Fischer-Tropsch synthesis, process A (FT^a)	Electricity, steam, FT liquids	Wood gasification sent to gas turbine, one pass synthesis
Fischer-Tropsch synthesis, process B (FT^b)	Electricity, steam, FT liquids	Wood gasification sent to larger gas turbine, one pass synthesis
Fischer-Tropsch synthesis, process C (FT^c)	Electricity, steam, FT liquids	Wood gasification sent to product synthesis, one pass synthesis
Mixed alcohols synthesis (MA)	Electricity, steam, C1-C3 alcohols	Wood gasification sent to product synthesis, 76% recycle of syngas

To synthesize an IPPB, the optimization objective in Eq (3.35) is solved subjected to the constraints in Eqs (3.1) – (3.34) and Eqs (3.36) – (3.37). In this work, the annual operating time (OH) is taken as 330 d/y with a plant lifespan of 25 years at a given interest rate of 8% [101]. Note that the processing cost in Eq (3.37) includes annualized capital cost, operating cost and maintenance cost which are extracted from the calculations Larson *et al.* (2006) [100]. Note also that biofuel and electricity prices (given in **Table A1.4** in **Appendix 1**) are determined by Larson *et al.* (2006) [100], which are listed as independent parameters in the model. Thus, these values can readily revise based on current market prices for an updated profitability analysis. Next, the current work neglects the selling price difference between MP steam and LP steam [101]. A fixed value of USD 3.38×10^{-3}/kg of steam is taken as calculated by Sammons (2009) [101].

All supplementary data are provided in **Tables A1.1 – A1.4** in **Appendix 1**. Note that the conversion factors for each biorefinery pathway which include intermediates (i.e. syngas), products (DME, FT, MA) and energy (electricity, MP and LP steams are shown in **Table A1.2**. Note also that all alternative biorefinery designs were individually optimized to be energy (e.g. electricity, steam, etc.) self-sustaining. This implies bioenergy generated from biorefinery is firstly used to satisfy the energy demand of the biorefinery. Then, any excess bioenergy is considered for energy integration with pulp and paper mill or sold as revenue [100].

Besides, the following assumptions are made in an IPPB [48],

a. Freshwater is supplied to BSWS at 45°C (TF^{FW}) and is free of dissolved solids ($CF^{FW} = 0$)
b. Heat capacity of oxygen delignification reactor (C_P^{OR}) is assumed as 4 kJ/kg.°C
c. DS content entering BSWS is fixed at 20% and at 150°C
d. Upper limit of DS content leaving Washer 3 is 0.094% at 70°C
e. Total black liquor recycled back to EMCC is set at 2,000 kg/ton of pulp
f. Temperature leaving twin roll press, T^{TRP} is at 80°C and is preheated to 115°C (T^{OR}) prior to entering the oxygen delignification reactor
g. In the oxygen delignification reactor, the increase in the amount of lignin F^{DSOR}, is set at 29 kg/ton of pulp
h. Black liquor is concentrated to a minimum DS content of 80% in the MEE

Note that Eqs (3.6), (3.8), (3.14), (3.24), (3.25) leads to a non-linear programming (NLP) model. The NLP model is solved using a commercial optimization software LINGO v10 with Global Solver in a HP Pavilion DM4 Notebook PC, Intel® Core™ i5-2450M Processor (2.50GHz) and 8GB RAM. The Global Solver uses a branch-and-bound algorithm combined with linearization to obtain global optimum solution for non-linear models [102].

A global optimum solution is obtained with gross profit of USD 9.61 million/y, and its results tabulated in **Table 3.2**. The optimized network configuration of an IPPB is shown in **Figure 3.7**. From **Figure 3.7**, it is also noted that gasification with Fischer-Tropsch synthesis (FT^c) is selected to achieve the maximum economic performance at a production rate of 0.0726 m^3/ton of pulp. Concurrently, steam and electricity are generated as by product via a gas turbine. Based on the optimized result, all electrical power generated is to be sold to the grid. The optimized IPPB generates revenues of USD 5.85 million/y from products, USD 11.26 million/y from electricity sold to the grid and USD 2.88 million/y from MP and LP steams. On the other hand, costs incurred include freshwater at USD 2.06 million/y and processing cost of biorefinery pathway at USD 8.32 million/y.

As shown in **Table 3.2**, the fresh water consumption has decreased from 12,321 to 10,396 kg/ton of pulp, a 15.6% reduction compared to Chew *et al*. Note that freshwater is supplied only to Washer 3. This is because freshwater is needed at the Washer 3 to ensure the final DS limit is met before leaving BSWS. Based on the countercurrent operational mode of BSWS, it can be seen that filtrate stream of each washer is reused to either the shower or dilution point of the previous washer. In the base case design in **Figure 3.5**, it can be observed that WBL is generated from filtrate of the extended modified continuous cooker (EMCC), Diffuser 1, Washer 1 and Washer 2. However, in **Figure 3.7**, the optimized pulp and paper biorefinery only generates WBL from EMCC and Diffuser 1. This is indicative that filtrate of washers in the upstream section of BSWS are most contaminated with DS and thus has less opportunity to be reused.

Table 3.2. Results of optimized integrated pulp and paper biorefinery

	Base Case BSWS	**Integrated Pulp and Paper Biorefinery**
Gross profit (million USD/y)	-	9.61
Revenues		
from products (million USD/y)	-	5.85
from electrical power (million USD/y)	-	11.26
from steam (million USD /y)	-	2.88
Costs		

from freshwater (million USD /y)	-	2.06
from energy (million USD /y)	-	0.00
from processing (million USD /y)	-	8.32
FT production (m^3/ton of pulp)	-	0.0726
Freshwater consumption in BSWS (kg/ton of pulp)	12,321	10,396
Total steam consumption (kg/ton of pulp)	2,420	-
Total steam production (kg/ton of pulp)	-	6424
LPS to be sold (kg/ton of pulp)	-	4246
MPS to be sold (kg/ton of pulp)	-	57
MPS allocation to BSWS (kg/ton of pulp)	-	2121

Other than that, the IPPB also generates sufficient process steam to satisfy its heating demand. Process steam is generated at two different levels, i.e. MP steam (2,178 kg/ton of pulp) and LP steam (4,246 kg/ton of pulp). The solved case study reported a 12.4% reduction compared to Chew *et al.* in MP steam requirement in BSWS, from 2,420 kg/ton of pulp to 2,121 kg/ton of pulp. Steam integration was observed between BSWS with an integrated biorefinery where 2,121 kg/ton of pulp of MP steam was utilized in BSWS. Note that the produced energy is sufficient to meet the energy demand of MEE and oxygen delignification reactor. Next, the remaining process steam from the biorefinery, 57 kg/ton of pulp of MP steam and 4,246 kg/ton of pulp LP steam is sold as revenue. Thus, it can be concluded that the model formulated was capable of synthesizing an IPPB which yields a high profitability while concurrently reducing the overall fresh resource demand of water and steam. It is also noted that the optimization model has determined that black liquor gasification is the preferred biorefinery pathway compared to conventional combustion. This finding corroborates previous experimental studies done on the techno-economic feasibility of black liquor gasification.

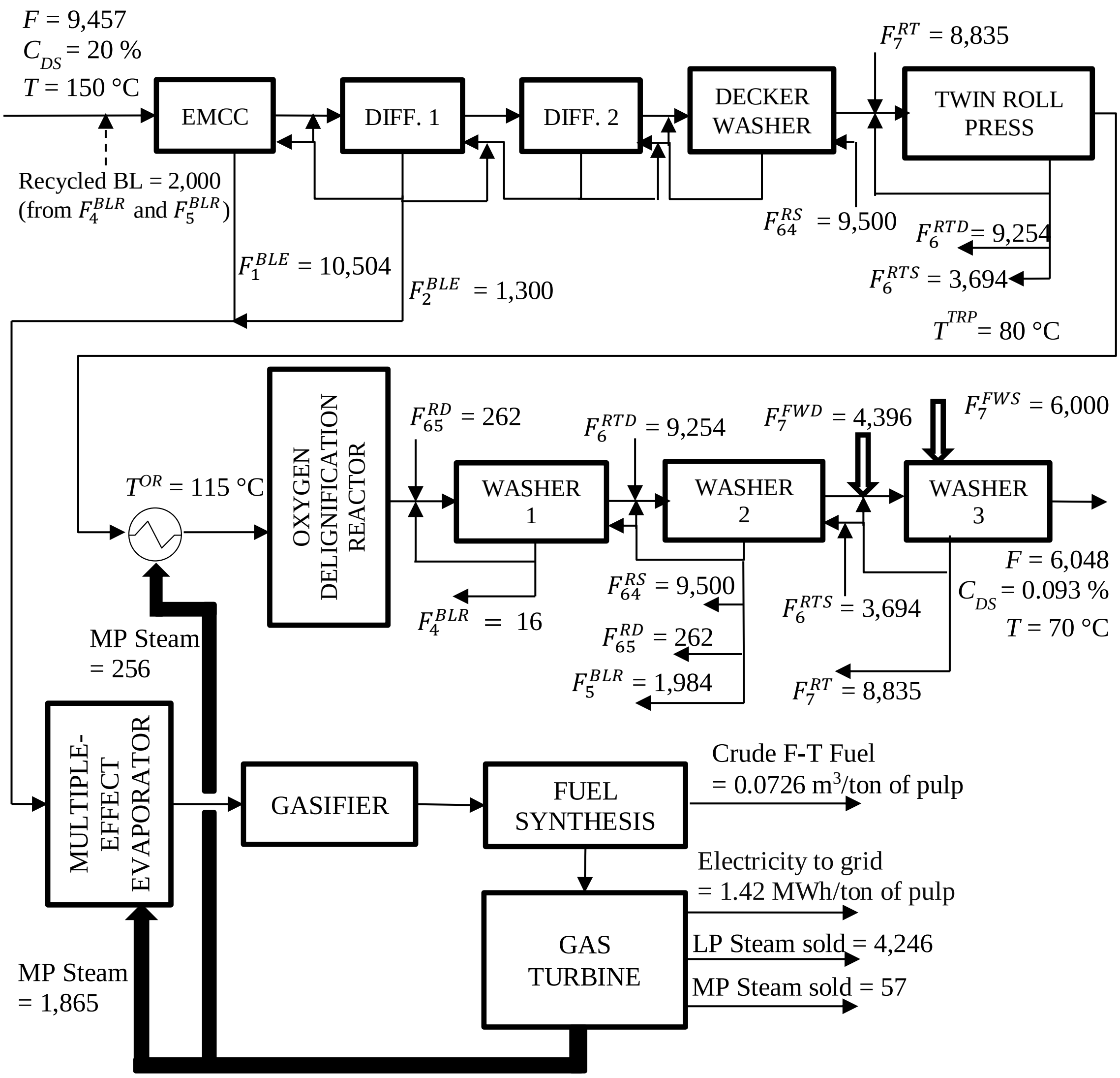


Figure 3.7. Optimized process flow of BSWS with biorefinery

(All flow rates are in kg/ton of pulp unless reported otherwise)

3.6. Sensitivity Analysis

The previous section presented the synthesized IPPB, solved for maximum economic performance. Gasification with FT[c] synthesis is the selected optimum biorefinery pathway with heat and power being generated as by-product. Next, sensitivity analysis is performed to explore potential system improvements in the mathematical model. It is desired to explore whether the optimization objective of the formulated model can be improved. This is done by firstly determining the most significant parameters in the mathematical model.

Note that the selection of the parameters was determined based on the *Reduced Cost,* which is obtained from the solution report of LINGO. Essentially, the *Reduced Cost* of a parameter relates the significance of the said parameter towards the optimal solution. A parameter with a larger *Reduced Cost* will have a higher effect on the optimal solution. *Reduced Cost* values reported in LINGO results found that biofuel prices affect the solution significantly [103]. In this work, two parameters are chosen in the sensitivity analysis, first is the biofuel (i.e. DME, FT and mixed-alcohol) market price, while the second is the number of washers in BSWS.

3.6.1. Effect of Biofuel Market Price

Firstly, the effect of a change in biofuel market price towards the selection of biorefinery pathway is examined. **Table 3.3** shows the optimized result of this analysis. Based on **Table 3.3**, it can be seen that the selected pathway will change from FT[c] to DME[a] when the market price of DME fuel is higher than USD 304/m^3. Note also that as the market price of Fischer-Tropsch fuel decreases to the threshold of USD 370/m^3, replacing the aging Tomlinson recovery boiler will be more economical viable as compared to incorporating the biorefinery into pulp and paper mill. Meanwhile, the market price of mixed alcohol fuels is found to be the least sensitive to market change as the biorefinery pathway remains unchanged for the price of USD 396/m^3 to USD 660/m^3.

Table 3.3. Sensitivity analysis of biofuel market price on gross profit

Biofuel	Biofuel price (USD/gal)	Biofuel price (USD/m^3)	Gross profit (USD/y)	Pathway chosen
Dimethyl Ether (DME)	0.85	225	9.62×10^6	FT[c]
	0.95	250	9.62×10^6	FT[c]
	0.99	261	9.62×10^6	FT[c]
	1.05	277	9.62×10^6	FT[c]
	1.15	304	11.94×10^6	DME[a]
	1.25	330	15.00×10^6	DME[a]
Fischer-Tropsch (FT)	1.40	370	9.11×10^6	TOM Boiler
	1.45	383	9.27×10^6	FT[c]
	1.50	396	9.46×10^6	FT[c]
	1.54	407	9.62×10^6	FT[c]
	1.60	422	9.84×10^6	FT[c]
	1.70	449	10.22×10^6	FT[c]

3.6.2. Effect of Number of Washers

Next, the number of washer is being varied to determine whether further freshwater savings can be achieved. Subsequently, the effect on the process steam demand in BSWS and the MEE is explored. An annualized washer cost, F^{washer} is included as an additional constraint in the NLP model and is described below. Eq (3.38) represents the annualized purchased washer cost adapted from Sinnott [104], assuming the washer is modelled as a vacuum drum filter.

$$F^{washer} = (\mathrm{a^w} + \mathrm{b^w S^n})(\mathrm{I^w})(\mathrm{AF}) \tag{3.38}$$

$$\mathrm{AF} = \frac{\mathrm{x(1+x)^y}}{\mathrm{(1+x)^y - 1}} \tag{3.39}$$

The parameters a^w and b^w are cost constants, S^n is the size parameter of the washer, I_w denotes number of washers present and AF is the annualized factor with x and y denoting interest rate and number of operating years, respectively. In this analysis, the DR of all washers in **Table A1.1** is fixed at 0.80 to allow for comparative analysis. The sequence of washer removal scenario is stated as below:

a. Scenario A: Eight washers (addition of Washer 4)
b. Scenario B: Base case of seven washers

c. Scenario C: Six washers (removal of Washer 3)
d. Scenario D: Five washers (removal of Washer 3, Washer 2)
e. Scenario E: Four washers (removal of final Washer 3, Washer 2, Decker Washer)
f. Scenario F: Three washers (removal of final Washer 3, Washer 2, Diffuser 2)

The cost function in Eq (34) is revised as below to incorporate washer cost:

$$COST = [\sum_k \mathrm{Y}_{kl} F_k^{SBL} P_{kl} + \sum_l \mathrm{Y}_{k\prime l\prime} F_{lk\prime}^{INT} P_{k\prime l\prime} + F^{FW} P^{FW} + Q^{TOT} P^Q + F^{washer}] \times \mathrm{PR} \times \mathrm{OH} \quad (3.40)$$

To perform the sensitivity analysis, the objective function in Eq (3.35) is solved subjected to Eqs (3.1) – (3.34) and Eqs (3.36), (3.38) – (3.40). **Table 3.4** tabulates the optimized results obtained. Note that the selection of biorefinery pathway is not sensitive towards the change in number of washers (i.e. FT^c for Scenarios A – F). For Scenario A to Scenario D, it can be summarized that as the number of washers decreases, freshwater consumption in BSWS increases. This is because more freshwater is required to remove the same amount of DS from the pulp stream. Besides, the DR was fixed at 0.8, limiting the potential for further water reuse/recycle. Next, an interesting observation is found in Scenarios D, E and F. It is observed that with five washers or less, the amount of freshwater consumption remains constant but would require additional energy supply to meet the process steam demand of MEE and oxygen delignification reactor. It is also noticed that, the steam generated from biorefinery fails to meet the process steam demand of BSWS. The above analysis indicates that the number of washers present in BSWS plays a factor in determining the total amount of process steam that can be integrated from the biorefinery. Upon reaching a certain threshold of washers (five washers in this case study), there would a portion of steam demand that needs to be satisfied from an external source. From the analysis, it is therefore much preferable to synthesize an IPPB with an increase in number of washers than the base case BSWS. The reason for this is because the annualized washer capital cost in Eq (3.38) has little effect on the gross profit of the IPPB. The potential for profit gain through an increase in number of washers outweighs the cost of installing additional washer in BSWS. The analysis indicates no favourable outcome is achieved upon reduction of washers.

Table 3.4. Sensitivity analysis of number of washers on gross profit

Scenarios	No. of Washers	Freshwater Consumption (kg/ton of pulp)	Energy Requirement (MJ/ton of pulp)	Gross profit (USD/y)	Pathway chosen
A	8	9,728	0	9.28×10^{6}	FT[c]
B	7	9,966	0	9.27×10^{6}	FT[c]
C	6	10,749	0	9.18×10^{6}	FT[c]
D	5	12,013	719	8.34×10^{6}	FT[c]
E	4	12,013	870	8.04×10^{6}	FT[c]
F	3	12,013	875	8.03×10^{6}	FT[c]

3.7. Conclusion

In this work, a systematic approach for the synthesis of resource conservation networks in an integrated pulp and paper biorefinery is proposed. A mathematical model was formulated which simultaneously considers the interaction between water and energy (in the form of process steam) consumption in an IPPB. Concurrently, the model also accounts for optimal generation of biofuel and bioenergy via direct combustion or gasification. An illustrative case study was presented for an existing brown stock washing system (BSWS) in a pulp and paper mill with freshwater and steam consumption of 12,321 kg/ton of pulp and 2,420 kg/ton of pulp, respectively. Based on the optimization result, Fischer-Tropsch (FT^c) synthesis was determined to be the most economically viable biorefinery pathway with heat and power being generated as by-products. The heat generated from the biorefinery was supplied back to BSWS to satisfy the process steam demands while any excess process steam was then sold as revenue. Future works could assess the sustainability of the synthesized IPPB by simultaneously considering for environmental impact and social development. The potential for carbon sequestration of bio-energy generated from the biorefinery can also be included. Besides that, mathematical tools such as fuzzy analytical hierarchy process (FAHP) can be adopted to address both the qualitative and quantitative factors that are inherent during the decision making process. These factors can include safety concerns and market volatility.

Chapter 4: An Optimization Model for the Synthesis of a Sustainable Eco-Industrial Park

4.1. Summary

The establishment of eco-industrial parks (EIPs) has been regarded as a sustainable approach in solving environmental issues, including the energy crisis. Environmentalists have further recognised the formation of EIP as one of the effective solutions for waste minimization. In the context of industrial ecology, an EIP represents an urban industrial area where multiple industries cooperate together through the exchange of material and energy. The higher interchange of material and energy streams leads to a greater ownership over the process, resulting in greater fresh resource savings as compared to unilateral initiatives. Recent literature has reported various quantitative measures to design and implement an EIP. For instance, eco-connectance (C^{E}) has been proposed to quantify the level of connectivity in an EIP. C^{E} is defined as *the ratio of the number of actual linkages over the maximum number of potential linkages* in an EIP. In the previous works, high level of C^{E} is desirable to maximise resource savings. Essentially, C^{E} can be used as an index to quantify the environmental performance of an EIP. However, the effect of C^{E} on the economic performance in an EIP has not been well studied. In this work, an optimization approach is developed to analyse the relationship between eco-connectance against the economic performance of an EIP. A hypothetical EIP network is synthesized to illustrate the proposed approach. Based on the result, it is noted that with a high eco-connectance, the resulting payback period of the EIP would be higher. This is a result of a higher number of participating industries, thereby increasing the initial capital expenditure.

4.2. Introduction

In a conventional eco-industrial park (EIP), multiple industries engage with each other for the exchange of material and energy streams. Often, the waste and by-product of one industry can be utilized as raw materials for another industry, forming an industrial symbiosis. Consequently, this would reduce the overall fresh resource requirement. Given the high level of integration between process streams among the industries, Hardy and Graedel (2002) proposed a quantitative index to determine the level of connectivity of an EIP, coined connectance (C) [105],

$$C = \frac{L}{\mathrm{S}(\mathrm{S}-1)/2} \tag{4.1}$$

where L is the number of links (or streams exchanged) between industries and S is the number of industries in an EIP. Connectance can be defined as "the ratio of the number of actual linkages to the number of potential linkages" in an EIP. The index draws analogy from biological ecology, where instead of food links between organisms, the links would refer to the sharing of process streams in the context of industrial ecology. Next, Wright and co-workers highlighted another quantitative measure along with connectance, termed diversity [106]. Later, Tiejun (2010) classified the total number of linkages (L) into linkages for product flow (L^{P}) and linkages for by-product or waste flow (L^{E}) [107]. A revised index, termed eco-connectance (C^{E}), is then expressed specifically for L^{E}, as below

$$C^{\mathrm{E}} = \frac{L^{\mathrm{E}}}{\mathrm{S}(\mathrm{S}-1)/2} \tag{4.2}$$

In their work, it was hypothesized that an EIP should have as much connectivity among enterprises, thus increasing the amount of material and energy recycled [107]. A closer look at the relationship between C^{E} and L^{E} in Eq (4.2) suggests that a high eco-connectance can be achieved by maximizing the number of by-product and waste linkages between industries. Consequently, this would reduce the overall waste generated as more process streams are being traded within the EIP. As such, a higher C^{E} can improve the environmental performance of an EIP. Besides, Chew *et al.* (2011) optimized the water and energy network of a pulp and paper mill to improve resource efficiency [108], which was later extended by Lee *et al.* (2014) for an integrated pulp and paper biorefinery (IPPB) [109]. More recently, Ng *et al.* (2014) studied the stability of industrial symbiosis schemes based on the individual economic interests of all participating industries [33].

Nonetheless, eco-connectance does not relay any relationship with the economic performance in an EIP. This is evident in Eq (4.2), where eco-connectance does not report the magnitude (i.e. flow rate) of the process streams being traded. Clearly, as more participants are introduced into the EIP, it would require an initial capital investment into the EIP. As the implementation of EIP becomes more widespread, proper planning is critical to ensure optimum economic performance for all parties involved. In this work, an optimization approach is developed to analyse the relationship between eco-connectance against the economic performance of an EIP. A case study using a pulp and paper mill (PPM) is solved to illustrate the proposed approach.

4.3. Problem Statement

The problem statement of the current work is stated as such: It is desired to set up an EIP with a PPM as the core of the EIP network. First, biomass, $b \in B$ generated from PPM is sent to potential bioenergy or bio-product related industries $c \in C$, where it is converted into bio-product and by-products. Later, the bio-products and by-product streams has the potential to be sent to PPM or any of the industries. In this work, it is desired to maximise the number of linkages to synthesize an EIP with high eco-connectance. Linkages are present as biomass links (L^{B}) and by-product links (L^{BP}). Concurrently, the optimized EIP network is constrained by a pre-determined payback period to ensure a positive economic performance. The next section details the methodology used to formulate the mathematical model.

4.4. Methodology for Model Formulation

4.4.1. Material and Energy Balance

In a PPM, biomass b is produced (F_b^{B}) and sent to each industry c with a flow rate of F_{bc}^{B}. It is noted that PPM is not considered as a member in index c, but instead serves as a stand-alone plant producing biomass to all industry c.

$$F_b^{\mathrm{B}} = \sum_c F_{bc}^{\mathrm{B}} \qquad \forall b \qquad (4.3)$$

Next, Eq (4.4) and Eq (4.5) relates the conversion of biomass (F_{bc}^{B}) into product (F_c^{P}) and by-product (F_c^{BP}) for each industry c. $\mathrm{Y}_{bc}^{\mathrm{P}}$ and $\mathrm{Y}_{bc}^{\mathrm{BP}}$ denote the conversion factors, which relates the amount of output generated for a given process over a certain amount of input. In this work, each industry c does not generate any biomass b, but instead receives it from PPM to produce its output.

$$F_c^{\mathrm{P}} = \sum_b F_{bc}^{\mathrm{B}} \mathrm{Y}_{bc}^{\mathrm{P}} \qquad \forall c \qquad (4.4)$$

$$F_c^{\mathrm{BP}} = \sum_b F_{bc}^{\mathrm{B}} \mathrm{Y}_{bc}^{\mathrm{BP}} \qquad \forall c \qquad (4.5)$$

Besides, Eq (4.6) expresses the relationship for industries c generating process steam as their main product (F_{cd}^{PS}), where the index d represent steam header and $\mathrm{Y}_{bcd}^{\mathrm{PS}}$ is the conversion factor. Process steam can be extracted as medium pressure steam (MPS) or low pressure steam (LPS).

$$F_{cd}^{\mathrm{PS}} = \sum_b F_{bc}^{\mathrm{B}} \mathrm{Y}_{bcd}^{\mathrm{PS}} \qquad \forall c\ \forall d \qquad (4.6)$$

In this work, by-product generated from each industry c (F_c^{BP}) can be used as input material to other industries in the EIP. The index f denotes the industry sink requirement for the by-product (F_c^{BP}). Eq (4.7) relates the by-product source balance, where F_{cf}^{BP} denotes the allocation of by-product from industry source c to industry sink f while the excess is exported to an external party ($F_c^{\mathrm{BP\text{-}EXP}}$).

$$F_c^{\mathrm{BP}} = \sum_f F_{cf}^{\mathrm{BP}} + F_c^{\mathrm{BP\text{-}EXP}} \qquad \forall c \qquad (4.7)$$

Following this, the by-product sink balance ($F_f^{\text{BP-SK}}$) can be determined via Eq (4.8), where $F_f^{\text{BP-IMP}}$ denotes imported by-product.

$$F_f^{\text{BP-SK}} = \sum_c F_{cf}^{\text{BP}} + F_f^{\text{BP-IMP}} \qquad \forall f \qquad (4.8)$$

Next, an analogous source and sink balance for process steam at each steam header *d* can be expressed as Eqs (4.9) and (4.10), where the index *g* represents steam sink.

$$F_{cd}^{\text{PS}} = \sum_g F_{cdg}^{\text{PS}} + F_{cd}^{\text{PS-EXP}} \qquad \forall c \ \ \forall d \qquad (4.9)$$

$$F_{dg}^{\text{PS-SK}} = \sum_c F_{cdg}^{\text{PS}} + F_{dg}^{\text{PS-IMP}} \qquad \forall d \ \ \forall g \qquad (4.10)$$

4.4.2. Environmental Assessment (Eco-Connectance)

In this work, linkages in an EIP are formed when there is an exchange of biomass or by-product between PPM with an industry. As noted earlier, the presence of linkages can be used as an indicator of the environmental performance of an EIP. For instance, a number of biomass or by-product linkages implies that more waste are being reused in the EIP. Consequently, this reduces the overall fresh resource demand and waste generation. Given the relationship between eco-connectance (C^{E}) and linkages in Eq (4.2), the environmental performance of an EIP can then be assessed using C^{E}.

Next, the presence of a biomass linkage can be related through an inequality as presented in Eq (4.11). Here, $F_{bc}^{\text{B-MIN}}$ denotes the minimum biomass flow rate required while L_{bc}^{B} is a binary integer representing the biomass link. The minimum biomass flow rate is introduced to ensure a logical value of flow rate would be generated before it can be considered as a linkage. Thus, a linkage is present (L_{bc}^{B}= 1) when the biomass stream (F_{bc}^{B}) is greater than or equal to the minimum biomass flow rate constraint ($F_{bc}^{\text{B-MIN}}$), and vice versa.

$$\frac{F_{bc}^{\text{B}}}{F_{bc}^{\text{B-MIN}}} \geq L_{bc}^{\text{B}} \qquad \forall b \ \ \forall c \qquad (4.11)$$

Similarly, Eq (4.12) expresses the presence of a by-product link (L_{cf}^{BP}), analogous to Eq (4.11).

$$\frac{F_{cf}^{\mathrm{BP}}}{F_{cf}^{\mathrm{BP\text{-}MIN}}} \geq L_{cf}^{\mathrm{BP}} \qquad \forall c \quad \forall f \tag{4.12}$$

Subsequently, the total number of linkages in an EIP (L^{E}) can be determined via Eq (4.13).

$$L^{\mathrm{E}} = \sum_{c} \left(\sum_{b} L_{bc}^{\mathrm{B}} + \sum_{f} L_{cf}^{\mathrm{BP}} \right) \tag{4.13}$$

4.4.3. Economic Assessment

Then, the eco-connectance of an EIP can be determined as shown in Eq (4.2). In this work, payback period (*PP*) is used as a tool to determine the economic performance of an EIP. This is expressed in Eq (4.14), where *CAPEX* denotes total capital expenditure (USD) of an EIP and *PROFIT* is the profitability of an EIP (USD/y)

$$PP = {CAPEX}/{PROFIT} \tag{4.14}$$

CAPEX of an EIP can be represented by Eq (4.15) where $\mathrm{X}_{bc}^{\mathrm{CAPEX}}$ denotes the capital investment cost parameter for each industry *c*, which covers for the purchasing of equipments and the cost of installation. In this work, *CAPEX* of an EIP is computed based on how many industry *c* participates in the EIP. This is determined by the number of biomass linkages (L_{bc}^{B}) between PPM with industry *c*. For instance, in the presence of a biomass linkage (L_{bc}^{B}= 1), *CAPEX* for industry *c* would be calculated as the product of L_{bc}^{B} and $\mathrm{X}_{bc}^{\mathrm{CAPEX}}$.

$$CAPEX = \sum_{b} \sum_{c} L_{bc}^{\mathrm{B}} \mathrm{X}_{bc}^{\mathrm{CAPEX}} \tag{4.15}$$

Next, profitability is determined from the revenue generated and the incurred operating costs in Eq (4.16).

$$PROFIT = REVENUE - COST \tag{4.16}$$

Revenue generated from EIP consists of revenue from product (G^{P}) and the internal exchange of by-product (G^{BP}) and process steam (G^{PS}), with cost units of USD/y.

$$REVENUE = G^{\mathrm{P}} + G^{\mathrm{BP}} + G^{\mathrm{PS}} \tag{4.17}$$

The relationship for G^{P}, G^{BP} and G^{PS} can be determined via Eq (4.18) to Eq (4.20), where t^{OT} and t^{OH} denote operating time (s/h) and operating hour (h/y) of an EIP. The selling cost parameters are presented for product ($\mathrm{X}_c^{\mathrm{P}}$), by-product ($\mathrm{X}^{\mathrm{BP}}$ and $\mathrm{X}^{\mathrm{BP\text{-}EXP}}$), and process steam ($\mathrm{X}_d^{\mathrm{PS}}$ and $\mathrm{X}_d^{\mathrm{PS\text{-}EXP}}$).

$$G^{\mathrm{P}} = \sum_{c} (F_c^{\mathrm{P}} \mathrm{X}_c^{\mathrm{P}}) \mathrm{t}^{\mathrm{OT}} \mathrm{t}^{\mathrm{OH}} \qquad (4.18)$$

$$G^{\mathrm{BP}} = \sum_{c} \left(\sum_{f} (F_{cf}^{\mathrm{BP}} \mathrm{X}^{\mathrm{BP}}) + F_c^{\mathrm{BP\text{-}EXP}} \mathrm{X}^{\mathrm{BP\text{-}EXP}} \right) \mathrm{t}^{\mathrm{OH}} \qquad (4.19)$$

$$G^{\mathrm{PS}} = \sum_{c} \sum_{d} \left(\sum_{g} (F_{cdg}^{\mathrm{PS}} \mathrm{X}_d^{\mathrm{PS}}) + F_{cd}^{\mathrm{PS\text{-}EXP}} \mathrm{X}_d^{\mathrm{PS\text{-}EXP}} \right) \mathrm{t}^{\mathrm{OT}} \mathrm{t}^{\mathrm{OH}} \qquad (4.20)$$

Next, the operating cost of an EIP includes expenses for the by-product and process steam requirement. $\mathrm{X}^{\mathrm{BP\text{-}IMP}}$ and $\mathrm{X}_d^{\mathrm{PS\text{-}IMP}}$ denote the purchase cost parameter for imported by-product and process steam.

$$COST = \sum_{f} (F_f^{\mathrm{BP\text{-}IMP}} \mathrm{X}^{\mathrm{BP\text{-}IMP}}) \mathrm{t}^{\mathrm{OH}} + \sum_{g} \sum_{d} (F_{dg}^{\mathrm{PS\text{-}IMP}} \mathrm{X}_d^{\mathrm{PS\text{-}IMP}}) \mathrm{t}^{\mathrm{OT}} \mathrm{t}^{\mathrm{OH}} \qquad (4.21)$$

4.5. Case Study

In this work, a PPM is planning to set up a joint venture to form an EIP with five potential bioenergy or bio-product related industries, termed biorefineries. Each of the biorefineries receives PPM biomass and converts it into different bio-product and by-products. The five biorefineries considered are: a boiler plant (c = 1), an integrated gasification combined cycle (IGCC) plant (c = 2) and three different biofuel producing biorefineries; dimethyl ether (DME) biorefinery (c = 3), Fischer-Tropsch (FT) biorefinery (c = 4) and mixed-alcohol (MA) biorefinery (c = 5). To synthesize the pulp and paper based EIP network, the formulated optimization model in Eq (4.2) – Eq (4.21) is solved by setting the objective function as

Maximise $\quad C^{\mathrm{E}}$ (4.22)

subjected to $\quad PP \leq 5$ (4.23)

Table 4.1. Conversion factors and investment cost parameter for each biorefinery

	Boiler	IGCC	DME-Biorefinery	FT-Biorefinery	MA-Biorefinery
Conversion factors (from black liquor)					
Product, Y_c^P	-	-	0.0649	0.0265	0.0157
By-product, Y_c^{BP}	1.632	3.225	-	-	-
MPS (as product), Y_{cd}^{PS}	0.893	0.925	-	-	-
LPS (as product), Y_{cd}^{PS}	1.717	1.801	-	-	-
Investment cost parameter, X_c^{CAPEX} (USD million)	136	218	197`	170	232

Besides, the following assumptions were made:

a. Biomass is limited to a single source, i.e. black liquor generated from PPM at 50 kg/s (F_b^B).

b. Conversion factors (Y_{bc}^P, Y_{bc}^{BP}, Y_{bcd}^{PS}) and investment cost parameters (X_{bc}^{CAPEX}, X_c^P, X^{BP}, $X^{BP\text{-}EXP}$, X_d^{PS}, $X_d^{PS\text{-}EXP}$, $X^{BP\text{-}IMP}$, $X_d^{PS\text{-}IMP}$) for each of the biorefineries are adapted from Larson *et al.* (2006) and Sammons Jr (2009), which are tabulated in **Table 4.1** and **Table 4.2**.

c. Capital investment for each biorefinery is estimated based on the maximum capacity in the EIP.

d. The minimum black liquor flow rate ($F_{bc}^{B\text{-}MIN}$) and electricity ($F_{cf}^{BP\text{-}MIN}$) to generate a linkage is set at 3 kg/s and 1 MW.

e. The total number of participating industries in the EIP is six (S = 6). This consists of PPM and the five studied biorefineries, giving a maximum possible linkage of 15.

f. PPM consumes 35.14 kg/s of MPS, 67.6 kg/s of LPS and 60 MW of electricity.

g. Boiler and IGCC plant produce MPS and LPS as their main product and electricity as by-product.

h. Electricity demand for DME-biorefinery, FT-biorefinery and MA-biorefinery are 34.9 MW, 31.8 MW and 41.6 MW.

i. Operating time (t^{OT}) is 3600 s/h while operating hour (t^{OH}) of the EIP is 8330 h/y

Table 4.2. Selling and purchasing cost parameter for all product and by-products

Cost Parameter	Cost
Biofuel, X_c^P	
DME (USD/gal)	1.57
FT (USD/gal)	2.09
MA (USD/gal)	2.04
Process steam, X_d^{PS}	
MPS (USD/t)	9 (X_d^{PS}) and 10 ($X_d^{PS\text{-IMP}}$)
LPS (USD/t)	6 (X_d^{PS}) and 7 ($X_d^{PS\text{-IMP}}$)
Electricity, X^{BP} (USD/kWh)	0.09 (X^{BP}) and 0.010 ($X^{BP\text{-IMP}}$)

The mixed-integer non-linear programming (MINLP) model is solved using commercial optimization software LINGO v13 with Global Solver in a HP Intel(R) Core(TM) i5-2400 CPU (3.10 GHz) and 4.00 GB RAM. A global optimum solution is reported in 5 seconds. **Figure 4.1** depicts the optimized EIP network, where PPM is to set a joint venture with a boiler plant, IGCC plant and a biorefinery producing DME. The reported eco-connectance, C^E is 0.467, consisting of three biomass links (L^B) and four by-product links (L^{BP}), resulting in a total linkage (L^E) of seven. Next, a payback period of 4.34 y is reported.

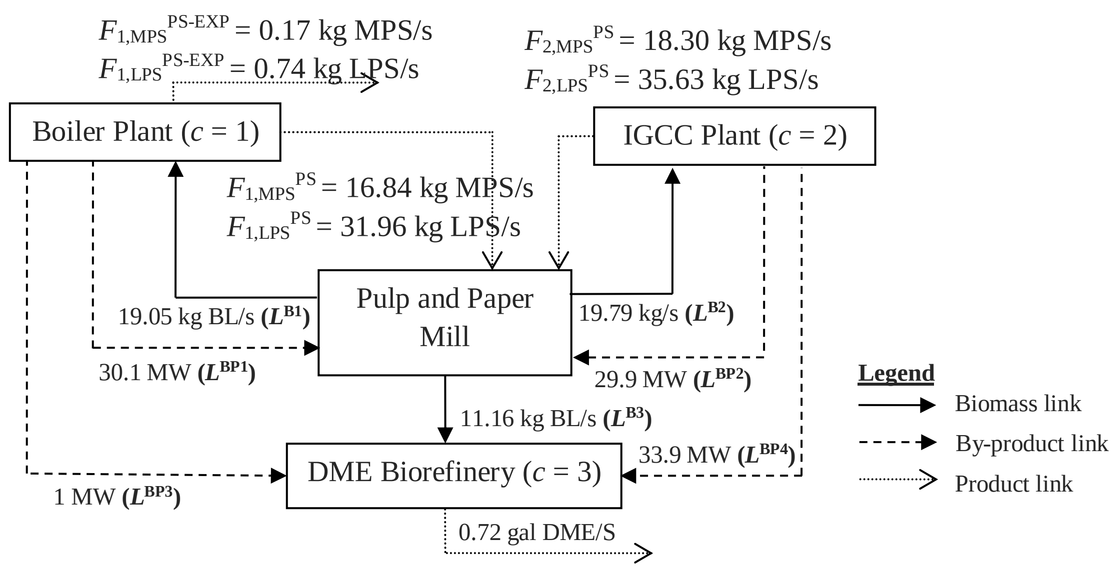


Figure 4.1. Optimized EIP network for PPM (Linkage labels are highlighted in **bold**)

As shown in **Figure 4.1**, black liquor generated is sent to the boiler plant (19.05 kg/s), IGCC plant (19.79 kg/s) and DME-biorefinery (11.16 kg/s). Next, both the boiler plant and IGCC plant generate process steam (i.e. MPS and LPS). In IGCC plant, all process steam produced is sent to meet the partial steam demand of PPM. The balance steam demand of PPM is then satisfied by the boiler plant. Subsequently, the boiler plant would generate an excess of process steam, which is sold to an external party (0.17 kg/s of MPS and 0.74 kg/s of LPS). Meanwhile, through the expansion of steam turbines in boiler plant and IGCC plant, electricity is generated as by-product. A total of four by-product linkages (L^{BP}) are present. PPM receives an electrical load of 30.1 MW from boiler plant and 29.9 MW from IGCC plant. Next, the electrical load balance from the boiler and IGCC plant is sent to satisfy the demand in DME-biorefinery. The low electrical load of 1 MW from boiler plant to DME-biorefinery is a result of the minimum electricity constraint ($F_{cf}^{\mathrm{BP\text{-}MIN}}$) set in Eq (4.12). Lastly, DME-biorefinery receives black liquor from PPM to generate 0.72 gal DME/s, to be sold as revenue. The utility demand of DME-biorefinery is supplied from boiler and IGCC plant.

Next, the relationship between maximum allowable payback period with the eco-connectance of an EIP is analysed through sensitivity analysis. The results are tabulated in **Table 4.3**. A trend is observed where, as the maximum allowable payback period increases from 2.5 y to 6 y, the eco-connectance increases from 0.13 to 0.67. It is concluded with an increase in the number of industry participation in an EIP, the eco-connectance increases. However, this would require a substantial amount of capital expenditure, resulting in a longer payback period for the EIP to generate a positive economic performance. Although a high eco-connectance is desired, the increased payback period may prove to be detrimental to the joint venture between PPM and biorefineries. Therefore, a compromise is needed to balance the economic and environmental performance of an EIP to ensure the joint venture is successful. Besides, from **Table 4.3**, it is found that a boiler plant and, in most scenarios an IGCC plant always participates in the EIP. This is driven by the process steam demand in PPM, which can only be supplied from boiler and IGCC plant. Next, the selection of biofuel producing biorefineries is dependent on the individual conversion factors and capital investment of each technology.

Table 4.3. Relationship between maximum payback period with eco-connectance of EIP

	Maximum allowable payback period (y)				
	2.5	**3**	**4**	**5 (Figure 4.1)**	**6**
Reported payback period, (y)	2.34	2.58	4	4.34	5.07
Eco-connectance, (C^E)	0.13	0.27	0.47	0.47	0.67
Biomass links, (L^B)	1	2	3	3	4
Number of industries	2	3	4	4	5
Participating biorefineries	Boiler	Boiler IGCC	Boiler IGCC FT-Biorefinery	Boiler IGCC DME-Biorefinery	Boiler IGCC DME-Biorefinery FT-Biorefinery

4.5. Conclusion

The current work has developed an optimization model which addressed the relationship between payback period with eco-connectance of EIP. As reported, although a high eco-connectance is desired to maximise the exchange of waste and by-product, the initial capital expenditure of introducing multiple industries might hinder the beneficial exchange of waste and by-product. Furthermore, an increased payback period would result in delayed profitability for the biorefineries as the initial capital expenditure needs to be firstly recuperated. Thus, it is concluded that a compromise is needed to balance the desire for both a high economic performance and environmental performance in an EIP. The information provided by this model would contribute towards business management, ecological study and environmental policy making. Future work could address the potential conflict which arise among the participating biorefineries with PPM. A strategic decision making (SDM) framework can be adopted to address this issue. Besides, study could also be done to minimize the financial risk associated with the eco-connectance in designing an EIP.

Chapter 5: A Systematic Game Theory-Based Stepwise Approach in the Synthesis of an Eco-Industrial Park

5.1. Summary

An eco-industrial park (EIP) employs the concept of industrial symbiosis to achieve sustainable development. By adopting a collective approach towards the sharing of resources and wastes, the potential economic and environmental performance of an EIP can exceed that of an enterprise operating unilaterally. However, the design of a sustainable EIP can be immensely complex, due to the inherent competition present among participating enterprises. This is particularly true when there is an unequal distribution of economic and environmental payoff among enterprises. Hence, a multiple-criteria decision making (MCDM) problem arises as each enterprise seeks to prioritize their self-interest and goals in any EIP initiative. This is further complicated when an external EIP authority is involved in the decision making process. Often, the desired EIP scheme by the EIP authority may not coincide with the interests and goals of the enterprises. Ultimately, this creates instability and renders the EIP unsustainable. To address this issue, this paper develops a systematic game theory-based stepwise approach as a framework for strategic decision making (SDM) in an EIP. The proposed framework seeks to identify a sustainable and stable EIP scheme. Here, three different game models are employed to resolve the MCDM problem between the participants. Concurrently, a fair distribution of economic and environmental payoff is determined to ensure stability. An EIP case study using a Kraft pulp mill as an anchor enterprise is used to illustrate the proposed approach.

5.2. Introduction

The framework of sustainable development emphasizes the following three aspects: economic, environmental and social [1]. In the industrial sector, eco-industrial parks (EIPs) have been noted for its positive impact in achieving sustainability. An EIP represents an industrial ecosystem where multiple enterprises engage with each other to share resources (i.e. material and energy), products and wastes [110]. This action allows for cooperative economic, environmental and social benefits. Industrial symbiosis is the core concept behind the operation of an EIP. It involves the physical exchange or integration of materials and energy between multiple enterprises [7, 8].

An EIP can be categorized by the means of which it emerges; either an *unplanned* EIP or a *planned* EIP. In *unplanned* EIPs, external factors drive individual enterprises to collaborate together and implement initiatives to improve their economic or environmental performances. The Kalundborg EIP has been documented as a successful exemplary of an *unplanned* EIP [7]. Next, in *planned* EIPs, deliberate planning is involved towards implementing an EIP. This is often governed by an EIP authority, which has the authoritative power to regulate the formation of an EIP. In planned EIPs, there is often an anchor enterprise; which represents the main focal point in any EIP. It is characterized by its ability to form multiple industrial symbiotic networks. As noted by Lowe (1997), the identification of an anchor enterprise is critical as it serves to attract other potential enterprises to join in the EIP initiative [7]. The author suggested that suitable anchor enterprises include Kraft paper mill (KPM), food processing plant and power station. In particular, various biorefinery technologies can be employed in KPM to convert KPM biomass into higher value-added products [88, 111, 112]. Van Heiningen (2006) noted the necessity for KPM to incorporate biorefinery to remain competitive in the market and reduce fossil fuel consumption [88]. Rafione *et al.* (2014) proposed an EIP using KPM as an anchor enterprise, termed a Green Integrated Forest Biorefinery (GIFBR). The GIFBR is characterized by minimum fossil fuel consumption, greenhouse gas emission, and waste [113].

There is continuing research being devoted to improve the performance of future EIP initiatives. In 2007, Tudor and co-workers presented a review on the current motivations and limitations of EIPs. The authors noted that EIPs offer significant improvement in the sustainability of enterprises when cooperative behaviour is enforced. At the same time, support should be present when planning an EIP, which include the government and the community [114]. Next, Tiejun (2010) introduced an index, termed *eco-connectance* to measure the degree of connectivity among enterprises in an EIP [107]. It relates the number of actual symbiotic connections present among enterprises over the maximum possible of symbiotic connections. Tiejun (2010) concluded that the index can be applied as a guide in the future planning and construction of EIPs.

On the other hand, Zhu *et al.* (2010) reported an indicator system as a means for EIP planning. The authors discussed the importance of controlling enterprise access into an EIP [115]. Zhu and co-workers argued that the selection of enterprises is crucial to ensure the stability and overall efficiency of an EIP. An EIP which is deemed unstable would not be able to sustain its operation in the long term. Next, Wang *et al.* (2013) addressed the issue of EIP stability by considering the distribution of symbiosis profit and symbiosis cost before and after the implementation of an EIP. In their work, stability of an EIP is linked to its economic performance and an EIP is said to be stable when there is a proportional share of additional costs relative to the profit gained by the symbiosis [116]. Later, Benjamin *et al.* (2014) introduced a criticality index and demonstrated it on a polygeneration plant and a bioenergy park (i.e. EIP). The index pinpoints the most critical unit operation of a system, which is crucial to prevent the occurrence of cascading failure across the entire EIP [117]. More recently, Boix *et al.* (2015) provided a comprehensive review on the optimization work done towards the design of an EIP [69]. The authors noted several research gaps, which include unequal power relationships between enterprises, multi-objective optimization with consideration of social aspects and uncertainties in energy being supplied to enterprises. Next, the earlier work by Wang *et al.* (2013) was incorporated in Ng *et al.* (2015) for the design of a palm oil based EIP. In their work, mathematical optimization was used with stability analysis to determine whether an additional enterprise should be included to an existing EIP [33].

Besides addressing the issue of EIP performance and stability, the implementation of any EIP initiative also brings with it a multiple-criteria decision making (MCDM) problem. A MCDM problem arises as each enterprise seeks to prioritize their individual interests over the collective interest of an EIP. Often, enterprises would select an EIP scheme which coincides with their highest individual payoff instead of one that could potentially generate a better *overall* payoff for all enterprises. Indeed, this is particularly true when considering economic payoff, where all enterprises would always pursue a business plan that generates the highest individual profit. Evidently, there have been EIP initiatives which did not materialize as a result of the failure to address the aforementioned MCDM issue [62, 63]. As such, the challenge lies in optimizing the symbiotic networks to ensure the interests of each enterprise are satisfied. Aviso *et al.* (2011) addressed individual interest using fuzzy optimization. Here, multiple objectives arising from multiple decision-makers are integrated into a single satisfaction parameter under predetermined constraints [32]. Other optimization models such as fuzzy optimization have also been developed [66, 67].

On the other hand, another approach towards resolving MCDM problem is game theory. It is the mathematical study of competition and cooperation between rational decision-makers. A game is defined as an interaction involving multiple players (i.e. decision makers), where each player's outcome (or payoff) is affected by the decision made by their opponents [68]. This interaction could be competitive in nature, where players prioritize their individual self-interest over their opponent's. Cooperative interaction instead involves players coordinating their strategies. In general, outcomes emerging from competition and cooperation would differ from each other. In the context of an EIP initiative, the enterprises and the EIP authority are essentially players in a game. Here, each enterprise adopts strategies which prioritize their individual self-interest, and each combination of strategies will result in specific payoffs. Given the possibility of different EIP schemes, the payoffs of each enterprise in each EIP scheme would differ. Besides, depending on the game model adopted, competitive or cooperative behaviours among the participants would also influence the MCDM solution.

Game theory has been developed extensively as a tool to analyse situations of interactive decision making, especially businesses [70, 71]. It has been applied in the design of an EIP with consideration to economic and environmental payoffs. Here, research work has been presented in water integration [72], heat integration [74] and industrial ecosystems [75]. Chew *et al.* (2009) considered two different game analysis, non-cooperative and cooperative game. Their proposed methodology was analysed for the interplant water integration (IPWI) scheme. The solutions for both games were later compared with the result from an optimization model. Their work highlighted how non-cooperative behaviour could hinder the selection of a global optimum solution (i.e. Pareto optimal) [72]. Cooperative game however, coincides with the global optimum while concurrently adhering to the self-interest of the enterprises. This work was later extended in Chew *et al.* (2011). Here, the authors included a centralized utility hub (CUB), which serves to regenerate all incoming wastewater from the enterprises and redistribute them as freshwater [73].

Besides, Aviso *et al.* (2010) noted that the interests between the enterprises and the EIP authority may not always be aligned. Often, the EIP authority is interested improving the overall performance of the EIP while the enterprises focus on their individual self-interests [31]. Aviso *et al.* (2010) addressed this issue by considering the mismatch of objectives between the enterprises and of the EIP authority. The authors incorporated the concept of a Stackelberg game to develop a fuzzy optimization model that considers the different levels of decision-making. In their water network case study, the EIP authority aims to minimize overall freshwater consumption while the enterprises aim to minimize cost for water treatment [31]. To reach the Stackelberg optimal, the authority influences the enterprises through the use of freshwater and wastewater fees and subsidies. The previous work was then extended by adapting the role of the authority as a centralized utility hub (CUB) instead [118].

The literature reviewed above has noted that for an EIP to be sustainable and stable, there is a need to resolve the MCDM issue while ensuring fair distribution of payoff among participants. An optimal solution would need to coincide with the interests and goals of all the participants in the game (i.e. enterprises and the EIP authority). Hence, it is the objective of this work to resolve the aforementioned issue. A systematic game theory-based stepwise approach is proposed as a framework for strategic decision making (SDM) in an EIP. The proposed stepwise approach employs three different game model, namely non-cooperative game, cooperative game and Stackelberg game. A case study anchored around a Kraft pulp mill (KPM) is used to illustrate the proposed approach.

5.3. Problem Statement

In this work, a *planned* EIP initiative is proposed for a given number of enterprises ($c \in C$). Each enterprise is governed by its own material and energy flow. A number of EIP schemes ($h \in H$) can then be generated through different industrial symbiotic networks. A MCDM problem is present where an optimal EIP scheme is to be determined, subjected to the sustainability and stability of an EIP. In this work, a sustainable EIP is defined as such where the predefined economic and environmental goals have to be satisfied for all enterprises. In addition, the effect of an EIP authority has on the decision making process would also be studied. Ultimately, a mutually agreeable EIP scheme (i.e. sustainable) for all participants would need to be determined or it may render the EIP initiative unstable. A systematic stepwise methodology using game theory is proposed, which considers how different game models can influence the strategic decision making (SDM) process.

5.4. Methodology for Game Theory Stepwise Approach

5.4.1. Preliminary Stage

The methodology for the selection of a sustainable EIP scheme is depicted in **Figure 5.2**; divided by a preliminary stage and a game theory stage. In the preliminary stage, a *planned* EIP initiative is proposed, where the participants include the number of enterprises ($c \in C$) and the EIP authority. In this work, enterprises are characterized as industrial based systems. Here, the material and energy flows (both input and output flows) for each enterprise c are determined. Given that each enterprise is an industrial based system; a common commodity being traded can be identified, which is the energy demand. This can be supplied from a combined heat and power plant (CHP). Hence, there are a number of options available for the CHP to allocate its product to the enterprises. This flexibility is used as a basis in the methodology to develop different EIP schemes. This relationship can be governed mathematically, where the total number of possible EIP schemes, H for c enterprises is given as

$$H = 2^{c-1} \tag{5.1}$$

Eq (5.1) states that for an EIP comprise of three enterprises (c = 3); where one of the enterprises is a CHP, the total number of possible EIP schemes is four (H = 4). This is depicted in **Figure 5.1**.

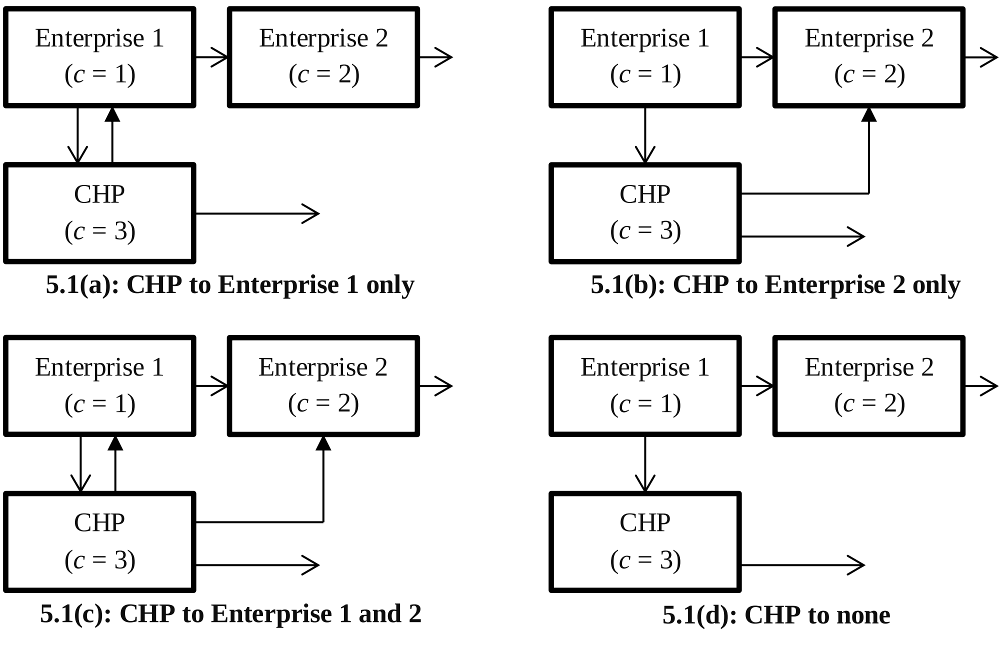


Figure 5.1. The total number of possible EIP schemes with three enterprises

Following this, the sustainability of each EIP scheme is determined by calculating the economic payoff and environmental payoff. In game theory, a *payoff* refers to an outcome resulting from the participation or strategy of any players (i.e. enterprise) in a game. The economic payoff is based on annual symbiosis profit (SP_c), expressed in USD/y. It is defined as the difference in profitability of an enterprise c before and after joining an EIP initiative. In Eq (5.2), SR_c and SC_c are the symbiosis revenue and symbiosis cost for enterprise c, respectively.

$$SP_c = SR_c - SC_c \qquad \forall c \qquad (5.2)$$

Symbiosis revenue (USD/y) refers to the additional revenue received when an enterprise enters the EIP initiative. This is expressed in Eq (5.3), where F_{cp} and C_p denote the flow rate and unit cost of each product p, respectively.

$$SR_c = \sum_{p=1}^{P} F_{cp} \mathrm{C}_p \qquad \forall c \qquad (5.3)$$

Eq (5.3) denote the symbiosis cost (SC_c) for each enterprise c. It is the additional cost incurred from the purchase of raw materials and/or utilities. In Eq (5.4), the variables F_{cq} and C_q denote the flow rate and unit cost of each raw material and/or utility q, respectively.

$$SC_c = \sum_{q=1}^{Q} F_{cq} \mathrm{C}_q \qquad \forall c \qquad (5.4)$$

Following this, the environmental payoff uses the net CO_2 emitted by each enterprise c, as expressed in Eq (5.5). The variable F_{cr} denote the flow rate of a process stream from emission source r for enterprise c. Next, the EF_r denotes the CO_2 emission factor from emission source r. The proposed methodology considers two primary sources of CO_2 emissions; natural gas combustion (r = 1) and the use of electricity from national grid (r = 2).

$$CO_c = \sum_{r=1}^{R} F_{cr} \mathrm{EF}_r \qquad \forall c \qquad (5.5)$$

Once the payoffs of each enterprise in every EIP scheme are determined, the respective interests and goals are outlined by all the participants. As the interests and goals may not be aligned by all participants, a MCDM is present. The MCDM problem is resolved through game theory, where three different game models are adopted; namely non-cooperative game, cooperative game and Stackelberg game.

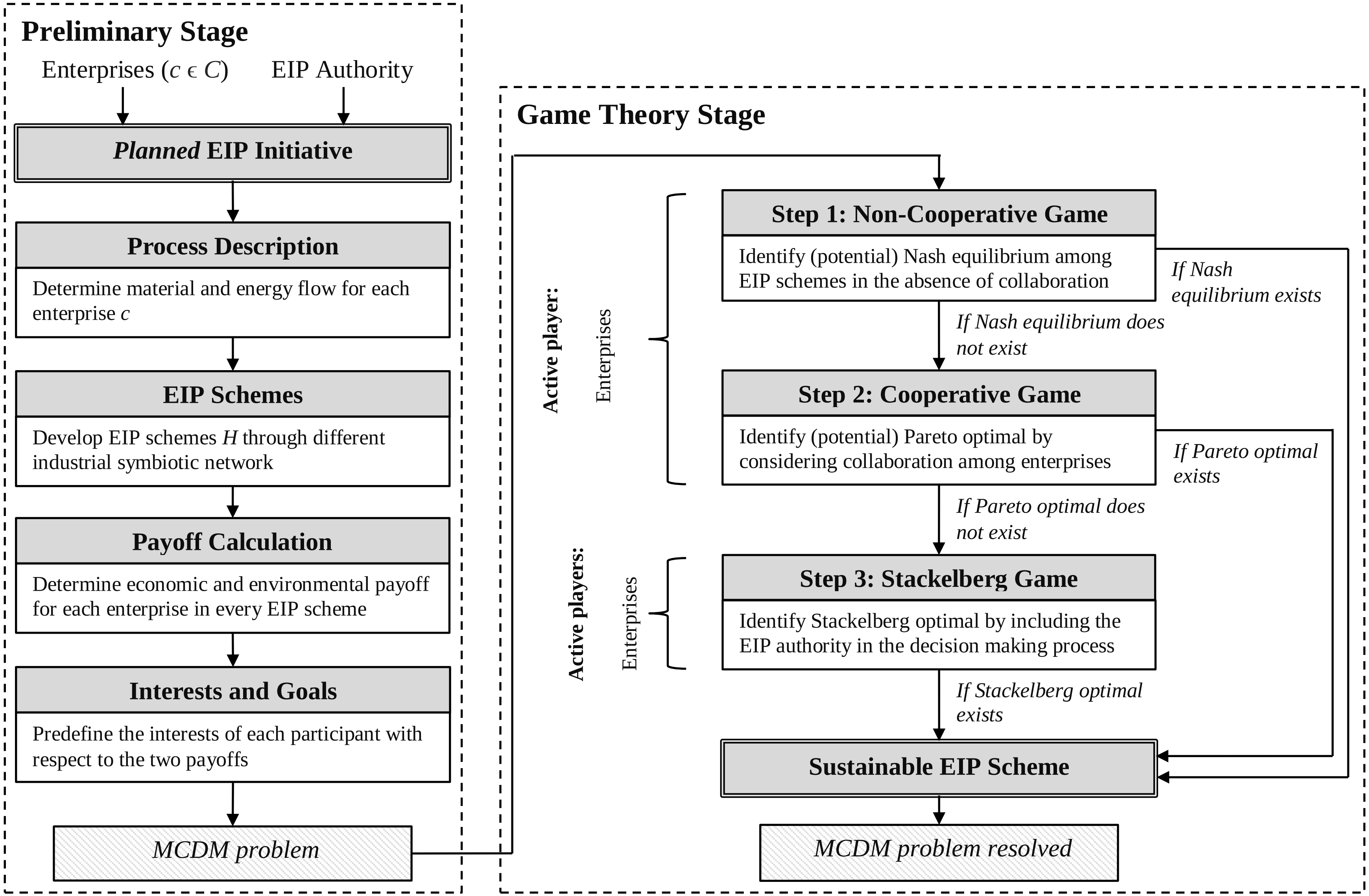


Figure 5.2. Methodology of a game theory-based stepwise approach to resolve MCDM problem in an EIP

5.4.2. Game Theory Stage

Step 1: Non-cooperative Game

Non-cooperative game seeks to identify the existence of an optimal solution (termed *Nash equilibrium*) in the absence of collaboration among players [70]. Nash equilibrium can be explained by considering the 2x2 payoff matrix in **Figure 5.3**. It depicts two players (Player 1 and Player 2) each with two different strategies (Strategy A and B). It is the goal of both players to maximize their individual payoff. If Player 1 adopts Strategy A, the best response for Player 2 is to adopt Strategy B (as 4 > 3). Next, if Player 1 adopts Strategy B, Player 2 would response by adopting Strategy B as well (as 2 > 1). Similarly, the response of Player 1 to each of Player 2's action is determined. If Player 2 adopts Strategy A, the best response for Player 1 is to adopt Strategy B (as 4 > 3). Next, if Player 2 selects Strategy B, Player 1 would response by selecting Strategy B also (as 2 > 1).

Nash equilibrium coincides with any strategy that results in the best payoff for both players. In this case, the Nash equilibrium is (2, 2); when both players select Strategy B. Note that if both players had collaborated and selected Strategy A instead, they would have had a higher payoff (3, 3) than the Nash equilibrium (2, 2). However, the strategies chosen earlier by each of the player were always Strategy B (in response to the opponent player's strategy). Thus, there was not an incentive for either player to deviate from Nash equilibrium to gain an advantage over the other player (i.e. solutions (1, 4) and (4, 1) will always be suboptimal).

		Player 2	
		Strategy A	Strategy B
Player 1	Strategy A	(3, 3)	(1, 4)
	Strategy B	(4, 1)	(2, 2)

Figure 5.3. 2x2 Payoff matrix

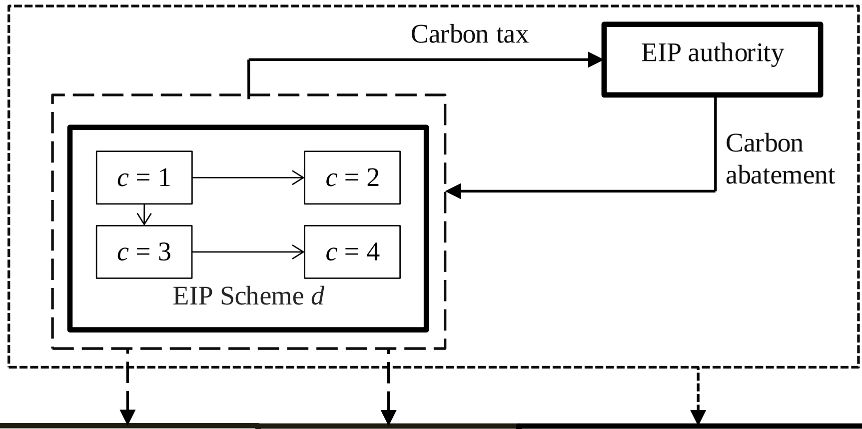
In the context of an EIP, the active and passive players in non-cooperative game are the enterprises and the EIP authority, respectively. Here, enterprises do not make binding commitment with each other, nor would they coordinate their strategies. From the EIP schemes developed, each enterprise would need to consider the strategies (i.e. payoffs) of their opponent. They would then counter respond by selecting the strategy that aligns with their individual self-interest (i.e. maximize individual economic payoff). If the final strategy of all the enterprises coincide with an EIP scheme (if any), that would be the Nash equilibrium.

Step 2: Cooperative Game

Cooperative game examines the existence of an optimal solution (termed *Pareto optimal*) after collaboration among players. Pareto optimal refers to any outcome for which no player can be made better off without making the other player worse off [70]. Consider again the 2x2 matrix in **Figure 5.3**. In this game, enterprises collaborate to coordinate their strategies and report the best *overall payoff* in the payoff matrix. Clearly, (3, 3) is the Pareto optimal with an overall payoff of six. It can be seen that the overall payoff for the other strategies is always less than the Pareto optimal. Besides, note that Nash equilibrium did not coincide with Pareto optimal in **Figure 5.3**. This implies that the Nash equilibrium solution could sometimes be improved upon to arrive at the Pareto optimal. Relating back to an EIP, the active players in cooperative game would be the enterprises while the EIP authority is still the passive player. In this game, enterprises need to coordinate their strategies together by evaluating the overall payoff of each EIP scheme. The Pareto optimal (if any) would coincide with an EIP scheme with the highest economic payoff.

Step 3: Stackelberg Game

Stackelberg game refers to a game model where a leader firm moves first and the follower firm(s) move sequentially. Here, the leader is in a position of power. The first move advantage allows the leader to have leverage over the followers, thereby influencing the final game outcome. In an EIP initiative, the leader is the EIP authority while the followers are the enterprises, where both are active players in the game. The goal of the EIP authority is to leverage its position of power to influence the decision making process and achieve a *Stackelberg optimal*. In the proposed methodology, Stackelberg optimal would result in the selection of an EIP scheme with the optimal environmental payoff. This is achieve by introducing incentives to encourage enterprise participation and drive the decision making process towards the goal of the EIP authority. In this work, carbon tax and/or carbon abatement is introduced while the *Shapley value* is used to ensure fair distribution of the environmental payoff among the enterprises. The distinction between the three game models is shown in **Figure 5.4**.



Game model:	Non-cooperative game	Cooperative game	Stackelberg game
Active players:	Enterprises	Enterprises	Enterprises and EIP authority
Passive	EIP authority	EIP authority	None
Payoff:	Individual	Overall	Overall
Distribution:	Stability (if any)	Stability (if any)	Stability and Shapley

Figure 5.4. Illustration of the distinction between the three proposed game models

Stability Analysis

In **Figure 5.4**, stability analysis is performed to ensure equitable distribution of profit and cost among enterprises [116]. The asymmetric distribution coefficient (ADC_c) is used as a measure of an EIP stability. It represents a departure from the most stable status of an industrial system. Wang *et al.* (2013) noted that ADC_c should ideally be in the range from -1 to 1, subjected to agreement by all enterprises.

$$ADC_c = \frac{RS_c}{RS_h^{\mathrm{EIP}}} - 1 \qquad \forall c \forall h$$

(5.6)

In Eq (5.6), RS_c is the ratio of symbiosis revenue to symbiosis cost for enterprise c and RS_h^{EIP} is the ratio of symbiosis revenue to symbiosis cost for EIP scheme h. The expression for RS_c and RS_h^{EIP} is shown in Eq (5.7) and Eq (5.8).

$$RS_c = \frac{SR_c}{SC_c} \qquad \forall c \qquad (5.7)$$

$$RS_h^{\mathrm{EIP}} = \sum_{c=1}^{C} \frac{SR_c}{SC_c} \qquad \forall h \qquad (5.8)$$

Shapley Value

Besides, *Shapley value* is used as a method to ensure fair distribution of environmental payoff among enterprises. It is a method of dividing the gains or costs among players according to their individual contributions [71]. The expression of Shapley value is shown in Eq (5.9).

$$\phi_c(\upsilon) = \frac{1}{C!}\sum_{\pi}[\upsilon(P_c^{\pi} \cup c) - \upsilon(P_c^{\pi})] \qquad \forall c \qquad (5.9)$$

$\phi_c(\upsilon)$ denotes the Shapley value of enterprise *c*, *C* is the total number of players (i.e. enterprises) while υ denotes a characteristic function (or payoff) which maps every possible coalition of enterprises. A coalition in cooperative games refers to any group of players in the game. Next, π is the order of which enterprises join a particular permutation. The term "permutation" relates to the act of arranging enterprises into a particular order/sequence. The expression "$\upsilon(P_c^{\pi} \cup c) - \upsilon(P_c^{\pi})$" is the marginal contribution of enterprise *c* in each permutation π [119]. Essentially, the Shapley value is then the *average* marginal contribution of enterprise *c* across all permutations. Consider a cooperative game consisting of players A, B and C. The number of possible coalitions that can be mapped is eight (2^3). Assuming the characteristic functions for each coalition is as below:

υ(A) = 11;

υ(B) = 7;

υ(C) = 8;

υ(A, B) = 15;

υ(A, C) = 14;

υ(B, C) = 13;

υ(A, B, C) = 20;

The Shapley value is shown in **Table 5.1**. Note π is 3, resulting in 3! or 6 possible orders. The order ABC denote that Player A joins the permutation first, followed by Player B and Player C. The marginal contribution for order ABC can be determined by looking at the functions, $\upsilon(c)$. Note that the total contributions from all three players is twenty; which is the function υ(A, B, C). As Player A joins first, υ(A) = 11. Next, Player B joins the permutation, and the function for both players is υ(A, B) = 15. The marginal contribution of Player B is then four. Finally, the marginal contribution of Player C is determined based on the total payoff, υ(A, B, C). The Shapley value is then the average marginal contribution of each player across all orders (i.e. Player A is (11+11+8+7+6+7)/(3!)). The example concludes that Player A should be allocated a larger fair of the total payoff (8.33), which can be corroborated as the individual payoff of Player A is larger than the other players (11 > 8 > 7).

Table 5.1. Determination of Shapley value

Order (π)	**Marginal contribution of player,** $\upsilon(P_c^{\pi} \cup c) - \upsilon(P_c^{\pi})$			**Total payoff**
	A	**B**	**C**	
ABC	11	4	5	20
ACB	11	6	3	20
BAC	8	7	5	20
BCA	7	7	6	20
CAB	6	6	8	20
CBA	7	5	8	20
Shapley value	**8.33**	**5.83**	**5.83**	**-**

5.5. Case Study

5.5.1. Preliminary Stage

In this work, a planned EIP initiative is proposed, where the EIP authority seeks the cooperation of four enterprises. The enterprises considered are Kraft pulp mill (KPM), bioethanol refinery (BIO), gasification plant (GAS) and combined heat and power plant (CHP). Note that KPM is identified as the anchor enterprise, given its ability to generate different biomass [113]. Besides, it is assumed that the four enterprises are currently in existence and are operating independently. There is currently no symbiosis exchange among them. In the proposed methodology, it is desired to form an EIP through multiple symbiosis exchanges among the four enterprises. The proposed symbiosis exchanges in the EIP are shown in **Figure 5.5**. First, Kraft pulp mill (KPM) would extract a portion of the hemicellulose content from the wood chips. The pre-extraction process reduces the pulp yield by 2% [120]. Thus, additional wood chips are fed to ensure pulp production remains at 1000 t/d. The extraction liquor, termed pre-hydrolyzate liquor is then sent to bioethanol refinery (BIO). In BIO, pre-hydrolyzate liquor is processed into ethanol, with acetic acid and furfural generated as by-product [121]. Besides, KPM would also send black liquor to gasification plant (GAS) to generate syngas [100]. Syngas can then be sent to combined heat and power plant (CHP) to produce steam and electricity through combined cycle technology. The input and output flow across the EIP is tabulated in **Table 5.2**. In **Table 5.2**, the input flow refers to the additional material and utility required to generate the necessary output products.

Note that in KPM, black liquor is no longer sent to the conventional recovery boiler. Thus, the overall heat and power demand in KPM would need to be satisfied from the hog boiler and from the CHP. Hog boiler in KPM uses hog fuel, which is essentially wood and sawdust residue from the upstream process of KPM to generate supplementary heat and power. Besides, it is assumed the heat and power of CHP in **Table 5.2** is the net output, where energy integration had already been performed individually by the CHP. Moreover, additional natural gas is used in CHP as fuel to generate the necessary heat to supply to all enterprises across the EIP (see **Table 5.3**). The term *source* refers to energy generation while *sink* refers to energy consumption in the enterprises. **Table 5.4** tabulates the unit cost of material, utility and product used in the proposed EIP case study.

Table 5.2. Input and output data for the proposed four enterprises in an EIP initiative

Enterprise	Input flow			Output flow		
	Material/Utility	Value	Conversion factor	Product	Value	Conversion factor
KPM (c = 1)	Wood chips fed (total)	2173.9 t/d	-	Pulp	1000 t/d	0.46 t/t chip
	Wood chips (additional)	90.6 t/d	-	Pre-hydrolyzate	2557.5 t/d	1.176 t/t chip
	Wash water	2903 t/d	1.34 t/t chip	Black liquor	1750 t/d	0.81 t/t chip
	Anthraquinone	1.1 t/d	0.0005 t/t chip	Heat (hog boiler)	29.4 MW	-
	Green liquor	62.5 t/d	0.03 t/t chip	Power (hog boiler)	13.9 MW	-
	Heat (hemicellulose) extraction only)	24.8 MW	985.41 MJ/t chip			
	Heat (pulping)	129 MW	-			
	Power (hemicellulose) extraction only)	1.9 MW	0.00087 MW/(t chip/d)			
	Power (pulping)	63.4 MW	0.029 MW/(t chip/d)			

BIO (c = 2)	Pre-hydrolyzate	2557.5 t/d	-	Furfural	0.92 t/d	0.00036 t/t PH
	Sulfuric acid	70.1 t/d	0.0274 t/t PH	Ethanol	39.5 t/d	0.01544 t/t PH
	Lime (CaO)	34.8 t/d	0.0168 t/t PH	Acetic acid	31.6 t/d	0.01236 t/t PH
	Heat	5.8 MW	195.64 MJ/t PH			
	Power	5.6 MW	0.0022 MW/t et			
GAS (c = 3)	Black liquor	1750 t/d	-	Syngas	2954.4 t/d	1.688 t/t BL
	Air	496.5 t/d	0.284t/t BL	Green liquor	978.2 t/d	0.559 t/t BL
	Heat	10.7 MW	0.0061 MW/t BL			
	Power	13.4 MW	0.0077 MW/(t chip/d)			
CHP (c = 4)	Syngas	2954.4 t/d	-	Heat	140.9 MW	-
	Natural gas	238.9 t/d	-	Power	84.5 MW	-

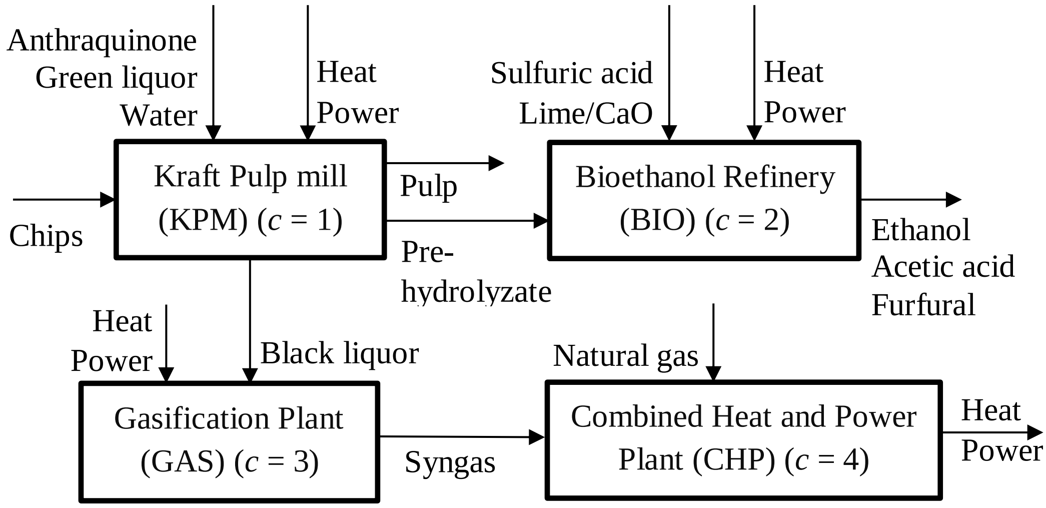


Figure 5.5. Proposed symbiosis exchange in the planned EIP initiative

Table 5.3. Heat and power demand in the planned EIP initiative

Enterprise	**Heat (MW)**			**Power (MW)**		
	Source	**Sink**	**Surplus/ Deficit**	**Source**	**Sink**	**Surplus/ Deficit**
KPM	29.4	153.8	-124.4	13.9	65.3	-51.4
BIO	0	5.8	-5.8	0	5.6	-5.6
GAS	0	10.7	-10.7	0	13.4	-13.4
CHP	140.9	0	140.9	84.5	0	84.5
Total	-	-	0	-	-	14.1

As outlined in the previous section, the next step is to develop different EIP schemes based off of **Figure 5.5**. Note that in **Figure 5.5**, energy demands for the enterprises are currently purchased externally. Given that there are four enterprises (c = 4), the total number of possible EIP schemes in this case study would be eight (H = 8) using Eq (5.1). The EIP schemes are developed by considering all possible symbiosis exchange between CHP with the other three enterprises. Specifically, the symbiosis exchanges considered are:

1) EIP01: Heat and power (CHP) to KPM
2) EIP02: Heat and power (CHP) to BIO
3) EIP03: Heat and power (CHP) to GAS
4) EIP04: Heat and power (CHP) sold to third party
5) EIP05: Heat and power (CHP) to KPM and BIO

6) EIP06: Heat and power (CHP) to KPM and GAS
7) EIP07: Heat and power (CHP) to BIO and GAS
8) EIP08: Heat and power (CHP) to KPM, BIO and GAS

Next, the economic and environmental payoff of each enterprise in each EIP scheme is calculated using Eq (5.2) - (5.5). **Table 5.5** tabulates the economic and environmental payoff results. The source of CO_2 emission in the studied EIP originates from combustion of natural gas. In this work, CO_2 emission that originates from biomass is considered carbon neutral and hence contributes to zero net CO_2 emission. In addition, the current work considers the user of national grid electricity to be accountable for the CO_2 emission. Finally, as noted in methodology earlier, the interest of enterprises in the EIP is to maximize economic payoff while the EIP authority aims to minimize environmental payoff.

Table 5.4. Unit cost data of material, utility and products (units are in USD/t unless specified otherwise)

Material/Product	Unit price
Chips	150
Anthraquinone	3307
Green liquor	10
Sulfuric acid	110
Lime/CaO	149
Pre-hydrolyzate	10
Black liquor	50
Furfural	1800
Ethanol	669
Acetic acid	1047
Syngas	68
Pulp	500
Wash water	0.3
Natural gas	0.0031 USD/MJ
Power (within EIP)	0.04 USD/kWh
Power (external)	0.12 USD/kWh
Steam (within EIP)	25
Steam (external)	28

Table 5.5. Economic and environmental payoff for eight EIP schemes

		EIP schemes							
	Enterprise	**EIP01**	**EIP02**	**EIP03**	**EIP04**	**EIP05**	**EIP06**	**EIP07**	**EIP08**
Economic payoff, SP_c (million USD/y)	**KPM**	135.55	94.16	94.16	94.16	135.55	135.55	94.16	135.55
	BIO	-0.35	3.64	-0.35	-0.35	3.64	-0.35	3.64	3.64
	GAS	23.35	23.35	32.60	23.35	23.35	32.60	32.60	32.60
	CHP	2.20	8.19	6.75	9.33	2.10	1.53	5.61	1.42
	Total	**160.76**	**129.33**	**133.16**	**126.49**	**164.63**	**169.33**	**136.00**	**173.21**
Environmental payoff, CO_c ($x10^4$ ton CO_2/y)	**KPM**	0	69.6	69.6	69.6	0	0	69.6	0
	BIO	4.7	0	4.7	4.7	0	4.7	0	0
	GAS	10.2	10.2	0	10.2	10.2	0	0	0
	CHP	13.0	0	0	0	15.1	16.8	0	18.9
	Total	**27.9**	**79.8**	**74.4**	**84.6**	**25.3**	**21.6**	**69.6**	**18.9**

5.5.2. Game Theory Stage

Step 1: Non-cooperative Game

In non-cooperative game, enterprises select the EIP scheme which coincides with their self-interest. This entails the selection of an EIP scheme with the highest individual economic payoff. In **Table 5.5**, KPM, BIO and GAS would report higher individual economic payoff when heat and demand is satisfied internally from CHP. On the other hand, CHP reports the highest economic payoff in EIP04. **Table 5.6** below tabulates the EIP preference for each enterprise. The symbol "✓" denotes an EIP scheme which is desired by enterprise *c*, while a "×" implies the enterprise has no desire to select the particular EIP scheme. Thus, as seen from **Table 5.6**, there is not an EIP scheme which coincides with the preference of all enterprises in any of the eight EIP schemes.

This is attributed to the difference in heat and power prices paid by enterprises to CHP or from a third party. In an EIP initiative, heat and power prices are set a lower rate than market prices to encourage industrial symbiosis. This results in reduced cost and increased profitability for KPM, BIO and GAS. In the absence of cooperation, none of the enterprises would be willing to unilaterally change their EIP preferences. Consequently, a Nash equilibrium solution could not be found in this game model. This shows that when competition arises among enterprises, the successful implementation of an EIP is unlikely. This outcome corroborated with the discussion by Chew *et al.* (2009), where an optimal outcome is hard to achieve in the absence of cooperation among players. The resultant MCDM problem is then addressed in the second game model; cooperative game.

Table 5.6. EIP preference among enterprises in non-cooperative game (with consideration to economic payoff)

	EIP preference of each enterprise							
Enterprise	**EIP01**	**EIP02**	**EIP03**	**EIP04**	**EIP05**	**EIP06**	**EIP07**	**EIP08**
KPM	✓	×	×	×	✓	✓	×	✓
BIO	×	✓	×	×	✓	×	✓	✓
GAS	×	×	✓	×	×	✓	✓	✓
CHP	×	×	×	✓	×	×	×	×

Step 2: Cooperative Game

In cooperative game, the interests and goals of the enterprises are to determine the EIP scheme which generates the highest overall economic payoff. From **Table 5.5**, the Pareto optimal scheme is found to be EIP08, with a maximum overall profit of USD 173.21 million/y. It is seen that EIP08 would result in the best economic payoff for all enterprises except CHP. Following the methodology developed earlier, the next step is to ensure the Pareto optimal EIP scheme is stable. **Table 5.7** tabulates the symbiosis profit (SP_c) and asymmetric distribution coefficient (ADC_c) of each enterprise. The asymmetric distribution coefficient and revenue-to-cost ratio for all enterprises can be calculated using Eq (5.6) and (5.7), respectively.

Table 5.7. Stability analysis of EIP08 before additional charges in commodity

	Economic payoff (USD million/y)			**Stability analysis**		
Enterprise	**Revenue, SR_c**	**Cost, SC_c**	**Symbiosis Profit, SP_c**	**Ratio, RS_c**	**ADC_c**	**Outcome**
KPM	202.31	66.77	135.55	3.03	0.62	Unstable
BIO	20.19	16.55	3.64	1.22	-0.35	Stable
GAS	69.52	36.92	32.60	1.88	0.00	Stable
CHP	79.20	77.78	1.42	1.02	-0.46	Unstable
Total	**371.23**	**198.02**	**173.21**	**1.87**	**-**	**Unstable**

If the asymmetric distribution coefficient for all enterprises (ADC_c) in an EIP scheme is within the predefined minimum and maximum ADC_c value, the EIP is considered stable. In this work, both the lower bound (ADC^{MIN}) and upper bound (ADC^{MAX}) of the asymmetric distribution coefficient have been set at -0.5 and 0.5 respectively, upon negotiation and discussion between the enterprises. **Table 5.7** shows that KPM stands to gain the most from the EIP initiative with an ADC of 0.62. BIO and CHP on the other hand would still report a positive economic payoff but has less to gain when joining the EIP initiative. To ensure the stability is within the predefined range of -0.5 and 0.5, the enterprise would need to renegotiate the prices of commodity traded among them. Specifically, the price of electricity is adjusted as it is the common commodity being traded among all enterprises. Here, an additional charge in electricity is varied by the CHP, resulting in increased cost to the other enterprises. The distribution of ADC among enterprises as the surcharge of electricity is placed is shown in **Figure 5.6**.

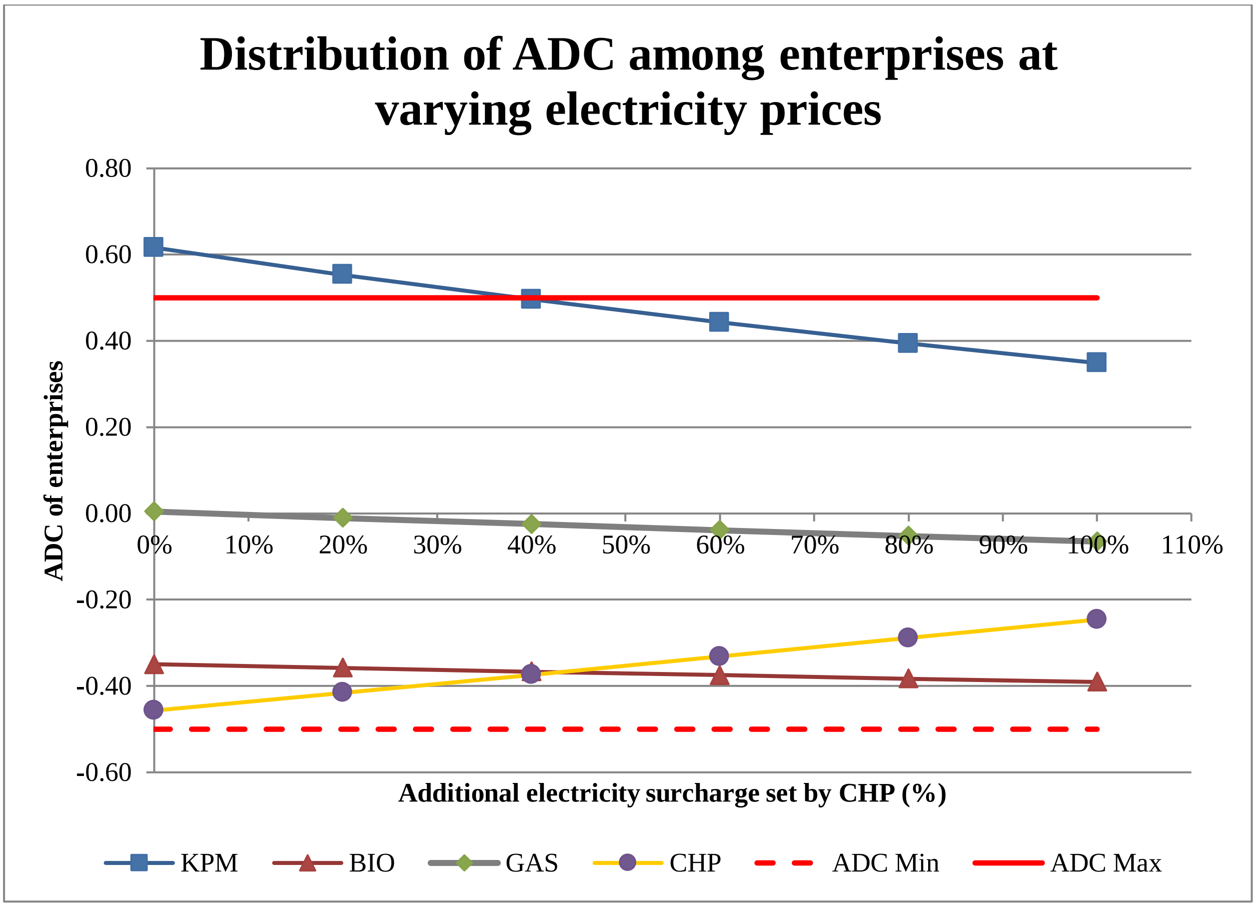


Figure 5.6. Distribution of ADC_c at varying electricity surcharge set by CHP

In **Figure 5.6**, it can be seen that by setting a higher electricity price from the CHP, the ADC_c of CHP can be improved. Concurrently, the incurred cost of the enterprises increases, resulting in a decrease in their individual ADC_c. By setting an electricity surcharge of 40% (USD 0.056/kWh), the ADC_c of all enterprises would fall within the predefined range of -0.5 to 0.5. Note that the additional charge for electricity is still lower than the purchased price from third party at USD 0.12/kWh. A comparison of the stability of EIP08 before electricity surcharge is placed can be viewed in **Table 5.8**.

Through cooperative game model, enterprises could ensure the stability in the EIP by redistributing the revenue and costs among them. In particular, as CHP is the bulk utility provider in the EIP, the price of electricity could help establish a stable EIP. Note that currently cooperative game only involves the enterprises as active player. Besides, emphasis is placed on the economic payoff of the enterprises and not the environmental payoff. As mentioned in methodology, an EIP authority has authority over the decision making process. In the next game model, it is desired to explore how the EIP authority could affect the decision making process from the Pareto optimal determined by the enterprises in cooperative game.

Table 5.8. Comparison of stability in EIP08 before and after enterprise negotiation

	Before negotiation			After negotiation		
Enterprise	**Symbiosis Profit, SP_c**	ADC_c	**Outcome**	**Symbiosis Profit, SP_c**	ADC_c	**Outcome**
KPM	135.55	0.62	Unstable	129.04	0.50	Stable
BIO	3.64	-0.35	Stable	2.92	-0.37	Stable
GAS	32.60	0.00	Stable	30.90	-0.02	Stable
CHP	1.42	-0.46	Unstable	12.12	-0.37	Stable
Total	**173.21**	**-**	**Unstable**	**174.99**	**-**	**Stable**

Step 3: Stackelberg Game

In the previous game model, cooperation among enterprises resulted in the selection of EIP08 as the Pareto optimal solution. However, no emphasis has been placed on the environmental performance of the EIP or the feedback from the EIP authority. In reality though, an EIP authority could significantly affect the decision making process through its authoritative power. Thus, in Stackelberg game model, the EIP authority participates in the decision making process by evaluating the environmental payoff of the EIP schemes. From **Table 5.5**, it can be seen that EIP08 results in the lowest environmental payoff at 18.9×10^4 ton CO_2/y. This is concluded to be the desired EIP scheme by the EIP authority. As the selected EIP scheme by the EIP authority coincides with the EIP scheme in cooperative game, EIP08 is deemed to be the Stackelberg optimal solution.

Nonetheless, EIP08 still results in the emission of CO_2, all attributed to CHP. Thus, the EIP authority would penalize EIP08 by setting a carbon tax on the CO_2 emissions. It is important to note that CHP is the currently the bulk provider of utility to all enterprises. When carbon tax is implemented, CHP would suffer the most from EIP08 as it is the sole enterprise generating net CO_2. This would result in increased cost being borne by CHP. As a rational business entity, CHP could easily withdraw from the EIP initiative and instead select the other EIP schemes which reports zero individual carbon emissions (**Table 5.5**). To prevent this, the EIP authority would need to allocate the CO_2 emission among the enterprises in EIP08, specifically to the end user of heat and power. This is achieved using Shapley value. From **Table 5.5**, the environmental payoff (or characteristic function, υ) can be expressed as below:

$$\upsilon(\text{KPM}) = 69.6;$$
$$\upsilon(\text{BIO}) = 4.7;$$
$$\upsilon(\text{GAS}) = 10.2;$$
$$\upsilon(\text{CHP}) = 0;$$

By applying Eq (5.9), the Shapley value for each enterprise in EIP08 is tabulated in **Table 5.9**. **Table 5.9** below compares the CO_2 emission for each enterprise before joining an EIP, after joining an EIP and after Shapley value allocation. Note that KPM is penalised the most as it is the enterprises consuming the highest heat and power (see **Table 5.3**). Thus, in cooperative game sense, the burden of the overall net CO_2 emission should be borne by KPM. Essentially, the levy to be paid to the EIP authority is borne by KPM instead of CHP. In **Table 5.9**, the negative CO_2 denote CO_2 abatement paid to the enterprises. Besides, a portion of the tax paid to the EIP authority is redirected to BIO, GAS and CHP as carbon abatement for having negative Shapley values. Note that the total environmental payoff before and after Shapley value distribution remains the same at 18.9×10^4 ton CO_2/y. Thus, the net carbon tax on EIP08 remains the same even after applying Shapley value. Next, from **Table 5.9**, it is interesting to note that through Shapley value, the CO_2 emission for all enterprises is reduced compared to base case. For instance, KPM would generate 69.6×10^4 ton CO_2/y if KPM decides to withdraw from EIP initiative. However, upon joining the EIP initiative, it is able to reduce its CO_2 emission by 23.6%.

Table 5.9. Distribution of CO_2 emissions in EIP08 (units are in x10^4 ton CO_2/y)

	Without EIP initiative (base case)	With EIP initiative	
		Cooperative game	**Stackelberg game**
Enterprise	Default CO_2 emission	Default CO_2 emission	Allocated CO_2 emission
KPM	69.6	0	53.2
BIO	4.7	0	-11.6
GAS	10.2	0	-61.9
CHP	0	18.9	-16.4
Total	**84.6**	**18.9**	**18.9**

Next, the individual economic payoff of the enterprises in EIP08 is adjusted following the allocated Shapley value. A positive Shapley value results in incurred cost and reduced profit, and vice versa. From **Table 5.9**, KPM will be penalized when the EIP authority implements carbon tax. Consequently, the tax rate imposed will have a significant influence on the overall stability of the EIP scheme. Thus, the EIP authority with its first move advantage can impose a carbon tax that could improve the overall stability of EIP08. Indeed, though carbon taxation, the stability of the entire EIP can be improved as seen in **Figure 5.7**. In fact, compared to the previous predefined ADC_c, the EIP authority could influence the game by ensuring an even more stable EIP (for instance a minimum and maximum ADC_c of 0.25 instead of 0.5. Specifically, at a carbon tax rate of \$58/t CO_2 to \$68/t CO_2, the ADC_c lies in the range of -0.25 to 0.25.

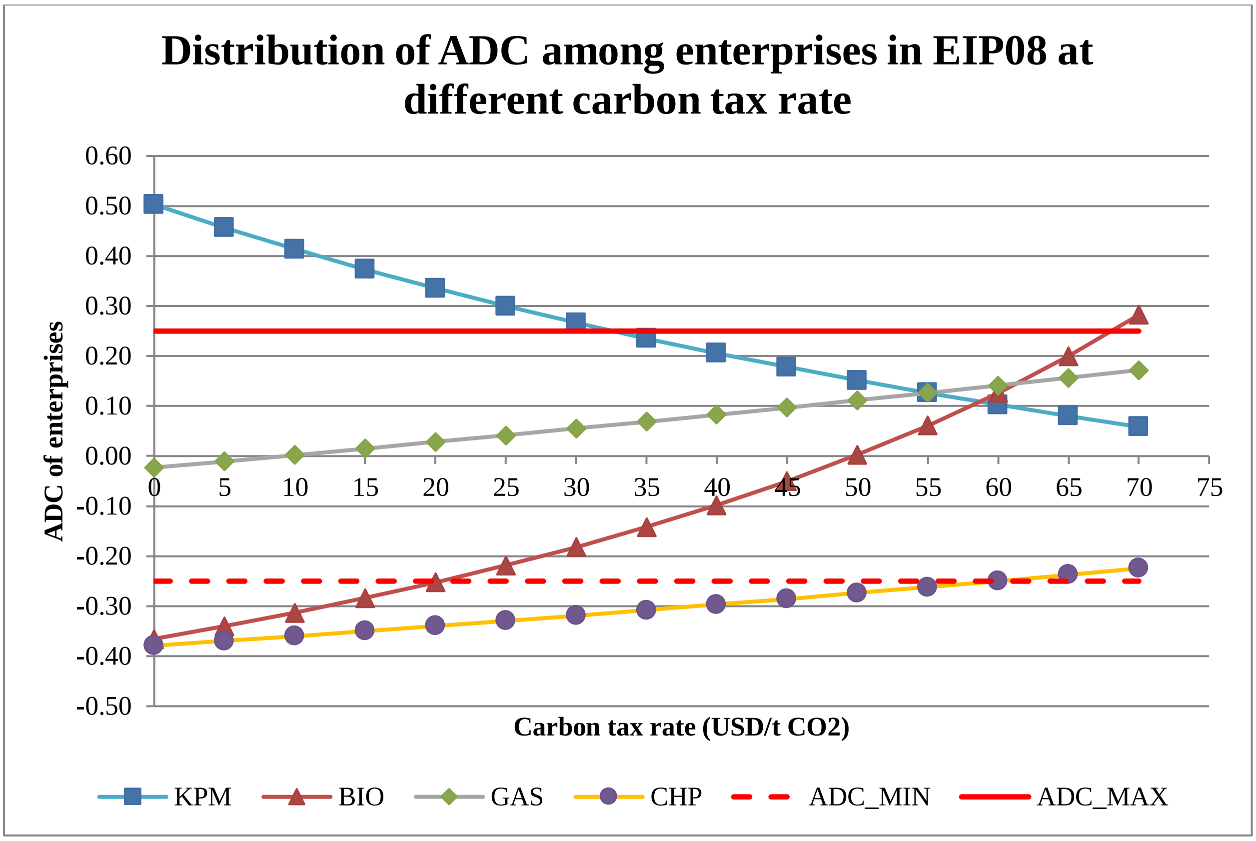


Figure 5.7. Distribution of ADC_c among enterprises in EIP08 at different carbon tax rate

Figure 5.7 shows the impact the EIP authority has on the overall stability of an EIP. From **Table 5.10**, with the intervention of the EIP authority through carbon taxation and abatement, the overall stability of the EIP08 has improved. Note that in Stackelberg game, BIO, GAS and CHP has reported increased profit. By comparison, in cooperative game, CHP is the sole enterprise making a loss if it selects EIP08 over the other EIP schemes. In Stackelberg game model, the EIP authority will no longer be an observer (i.e. passive player) but will participate as an active player together with the enterprises. Being the upper level decision maker, the authority can exercise its role as the regulator to influence the decision making process. With its first move advantage, it could encourage all enterprises to participate into EIP08 while ensuring a fair distribution of economic and environmental payoff. The proposed stepwise framework has identified EIP08 as the ideal scheme which is agreeable by all participants. The Stackelberg optimal also identified KPM as the anchor enterprise, where its ADC is highest among all other enterprises in the EIP.

Table 5.10. Comparison of stability in EIP08 before and after carbon tax and abatement

	With EIP initiative		Stability analysis	
Enterprise	Symbiosis profit before carbon tax/abatement	Symbiosis profit after tax/abatement	ADC before carbon tax/abatement	ADC after carbon tax/abatement
KPM	129.04	98.17	0.50	0.11
BIO	2.92	9.67	-0.37	0.10
GAS	30.90	34.50	-0.02	0.13
CHP	12.12	21.64	-0.37	-0.25
Total	**174.99**	**163.99**	-	-

Corporate and social responsibility as an anchor enterprise

A special mention is highlighted on the final outcome from Stackelberg game model. With collaboration, the final solution with the intervention of the EIP authority is both sustainable and stable (with respect to both payoffs). The only drawback is KPM reports a reduction in profit of 24%. In hindsight, KPM, as a business entity could still consider selecting this EIP scheme. There are several factors which could be justified for the reduction in profit in KPM:

- In cooperative game sense, KPM as the anchor enterprise could consider the reduction in its profit for the overall collective benefit of the EIP
- Without collaboration, KPM would report a higher environmental payoff compared to if KPM joined EIP08. Upon carbon taxation, it would incur a higher loss in comparison to EIP08
- The EIP authority can implement other policies to improve the economic performance of the EIP such that it will be favourable to the other enterprises. For instance, given KPM is the anchor enterprise, the EIP authority could provide rebate from the utilization of KPM biomass

The factors above combined with the leverage an EIP authority has as a leader, could convince KPM to join the proposed EIP initiative. Being an anchor, KPM would have further opportunity to expand the EIP network through additional symbiosis linkages.

5.6. Conclusion

In this work, a systematic game theory-based stepwise approach has been developed as a strategic decision making (SDM) tool for the selection of a sustainable and stable EIP scheme. Here, a sustainable and stable EIP is determined subjected to the economic and environmental payoffs of the enterprises. The incorporation of game theory allows for the conflict of interest between the EIP authority and the enterprises to be resolved. The proposed approach introduces three different game models in a stepwise manner, from non-cooperative game, cooperative game to Stackelberg game. These game models will reveal whether a mutually agreeable and sustainable EIP scheme can be achieved through Nash equilibrium, Pareto optimal or Stackelberg optimal, respectively. Apart from that, stability analysis and Shapley value method are also incorporated to ensure an equitable distribution of economic and environmental payoff among the enterprises. The developed methodology was applied in an EIP case study using a KPM as the anchor enterprise; which can be readily adapted for other forms of industrial systems. The findings of this work serve as a benchmark towards the implementation of future EIP. The proposed approach could be used as a preliminary screening tool to aid decision makers in screening desirable EIP schemes. Aside from that, future work could consider additional payoff (e.g. social considerations) and combining mathematical optimization models. This would inevitably be less cumbersome as compared to the analytical approach proposed in this work.

Chapter 6: An Optimization Approach to Resolve Multiple Decision Making in a Pulp and Paper Biorefinery

6.1. Summary

Biorefineries stemming from pulp and paper mills (PPMs) and other processes have been noted to offer improved economic and environmental performances. In such an industrial cluster, biomass from PPMs is processed into biofuel and bioproducts through different biorefinery technologies. Given the highly integrated material and energy networks, it is not uncommon for the industrial cluster to be operated by multiple enterprises. This gives rise to an eco-industrial park (EIP), where each enterprise acts as an independent decision maker. Here, the actions of each enterprise are driven by rational self-interest, capable of influencing the outcome of the EIP scheme. Thus, competition emerges to report the optimal EIP scheme, leading to a multiple criteria decision making (MCDM) problem. In this work, the MCDM problem is resolved through mathematical optimization and game theory. An EIP case study based on a PPM biorefinery is used to illustrate the proposed approach. Firstly, an optimization model was formulated which reported an EIP scheme with a positive overall economic payoff. However, there was an unequal distribution of economic payoff among individual enterprises. This is resolved by analyzing the individual payoffs through cooperative game strategy. Here, enterprises hold equal power in the EIP and coordinate their strategy together by varying the prices of goods/energy being traded between each other. In this work, two cooperative game scenarios are analyzed. The first scenario seeks to report a solution where each enterprise has a positive economic payoff while the second scenario aims to achieve a uniform internal rate of return.

6.2. Introduction

Pulp and paper mills (PPMs) are facing increased challenges in recent years. This can be attributed to a number of factors, from shifts in renewable energy policies to the changing consumer trend towards electronic media [15]. There is ongoing research devoted towards studying ways to improve the market penetration of PPMs. In particular, black liquor gasification (BLG) has emerged as an attractive alternative for the industry to diversify its product portfolio. In a PPM, black liquor is the most important biomass due to its high heating value, in the range of 13,000 – 15,500 kJ/kg [20]. Furthermore, the use of syngas from BLG for biofuel and bioproducts generation has been documented.

The incorporation of BLG as part of a biorefinery initiative has been noted to offer improved energy, economic and environmental performances. Earlier works by Eriksson and Harvey (2004) compared recovery boiler technology with BLG for different mill configurations (e.g. market pulp mills and integrated PPMs) [122]. It was reported that in all configurations, BLG remains the preferred option over conventional black liquor combustion. Next, Harvey and Facchini (2004) studied the performance of BLGCC based on two different gas turbine models. The authors estimated that the difference in power output between a simplified gas turbine model with a more sophisticated model (termed "off-design") was below 5% [123]. Besides, Harvey and Facchini (2004) also included comparison between two different black liquor usage strategies; either allocating all black liquor to combined heat and power (CHP) for electricity production or exporting the surplus black liquor.

A later work by Andersson and Harvey (2006) on BLGCC showed the potential for electricity export compared to conventional black liquor combustion [124]. This finding was promising as even though modern PPMs are self-sufficient with regards to steam requirement, it would still require the purchase of power from external sources. In 2006, Larson and coworkers [100] reported a comprehensive cost-benefit assessment for BLG in Kraft PPM. The authors compared between replacing an aging recovery boiler against eight potential biorefinery designs. Larson *et al*. (2006) concluded that the introduction of BLG entails a high capital investment, but would remain attractive given its higher energy efficiencies and increased product diversification [100]. Following this, Tay *et al*. (2011) formulated a fuzzy optimization model for the synthesis of an integrated biorefinery. The proposed model was capable of reporting an optimal solution by simultaneously considering the trade-off between economics and environmental impact [19]. This is achieved by maximizing a variable; the degree of satisfaction (λ), which is interdependent on the net present value (NPV) and environmental score.

Next, Wetterlund et al. (2010) concluded that the price ratio of fossil fuel to biomass and the capital cost of BLG influenced the level of economic policy support necessary to invest into BLG. In their work, a gasification based biorefinery producing DME was analysed, which was subjected to four different energy market scenario and two different capital recovery factor. Each market scenario is governed by two interdependent parameters, future fossil fuel prices and CO_2 charge levels (which influences the price of biomass) [125]. Their results are shown in **Table 6.1**. As observed, the level of biofuel support necessary is low (10 EUR/MWh) when fossil fuel prices are high and CO_2 charge levels are low. This creates strong incentives for investment into BLG, which would only require minimal support to be profitable. When examining the effect of capital recovery factor, it is noted that BLG is desirable when the initial investment cost is distributed over a longer period of time (low capital recovery).

Table 6.1. Level of biofuel support required to make investment in BLG profitable [125]

Year	**2009**	**2030**			
Scenario	Current	A	B	C	D
Fossil fuel price	High	Low	Low	High	High
CO_2 charge levels	Low	Low	High	Low	High
Base case biofuel support (EUR/MWh)	10	37	61	10	33
Biofuel support at higher capital recovery (EUR/MWh)	32	59	84	**33**	58

Next, Naqvi *et al*. (2010) published a review on the development of different BLG technologies in pulp and paper mills [89]. The authors justified several driving forces for BLG development; such as the need to replace the recovery boiler, the high heating value of black liquor, the higher electrical efficiency through BLG combined cycle (BLGCC) and the reduced fossil fuel dependency with biofuel substitution (e.g. methanol, dimethyl ether (DME)). Besides, the advantage of the biorefinery was also emphasized by Moshkelani *et al.* (2013). In their work, a methodology for energy optimization for the pulp and paper biorefinery was proposed. The methodology involves a stepwise approach which considers simulation of the base case, pre-benchmarking and evaluation of equipment performance, and analysis of system interaction. The authors concluded that future pulp and paper biorefinery would be highly integrated, requiring optimizing at the total site level [111].

Later, Rafione *et al*. (2014) reported an implementation strategy for the pulp and paper biorefinery, termed a Green Integrated Forest Biorefinery (GIFBR) [113]. Here, a GIFBR is implemented in phases, where a furfural biorefinery is firstly retrofitted to an existing Kraft mill. This is followed by the introduction of a gasification polygeneration unit. Next, several options for syngas utilization were also considered. By incorporating a phase by phase strategy, it was noted that the GIFBR was economical attractive as the high investment cost was distributed over the years. More recently, Lee *et al*. (2014) developed an optimization model for the synthesis of an integrated pulp and paper biorefinery (IPPB) [109]. The model maximizes the profitability of the IPPB considering different black liquor conversion pathways. The authors noted that the amount of steam and water savings in the washing stage would significantly affects the quality and quantity of black liquor generated, thereby driving the model to select the most profitable biorefinery pathway.

From the reviews above, it is noted that current work focused primarily on the operation of the pulp and paper biorefinery as a single enterprise. In such an industrial cluster, all decisions regarding the plant operation are governed by a single enterprise. However, it is not uncommon for the industrial cluster to be operated by multiple enterprises. This gives rise to an eco-industrial park (EIP), where multiple enterprises cooperate together through the collective exchange of material and energy. In an EIP, there is often a central or core enterprise, which serves as an anchor to provide the necessary material and energy exchange among the other participating enterprises. It is noted that a PPM can be selected as an anchor enterprise, from its access to abundant biomass and the products that it can supply to other enterprises (e.g. black liquor and hog fuel). Indeed, Pettersson *et al*. (2015) had begun to address for biofuel production from PPMs at a much larger scale; considering multiple pulp mills within the geographical vicinity of Sweden [61].

In an EIP, each enterprise would act as an independent decision maker, with the power to influence the outcome of the entire industrial cluster. Consequently, the feedback of each enterprise would need to be considered to achieve a mutually agreeable solution. This is known as a multiple criteria decision making (MCDM) problem. Various methodology and approaches had been developed in the literature to deal with the MCDM problem. One such approach is *game theory*, which is a mathematical study of cooperation and competition among rational and intelligent decision-makers. Here, a game is defined as any interaction between two or more players (decision makers) who make decisions that will influence each other's outcome [68, 69]. Thus, the operation of an EIP can be a viewed as a game, where the enterprises are the players, interacting with each other through different strategies. The different combination of strategies and games will then result in specific payoffs (or outcomes) for each enterprise.

Chew *et al*. (2009) were one of the earliest authors to adopt game theory analysis in process systems engineering [72]. The authors considered two different game analysis, non-cooperative and cooperative game. Their proposed methodology was analyzed on a case study of inter-plant water integration (IPWI) scheme. In non-cooperative game, players do not make binding commitment to coordinate their strategies while cooperative game refers to the coordination of strategies between the players. In their work, six different IPWI schemes were generated from three individual water networks. The authors concluded that in non-cooperative game, the optimal solution for each water network did not correspond to the global optimal solution. The findings highlighted how individual self-interest by one water network could influence the solution of the IPWI scheme. Nonetheless, by adopting cooperative game, the authors noted that the wastewater treatment costs were redistributed among the players to reach a globally optimal solution. Their work was later extended by Chew *et al*. (2011) to address for an IPWI with a centralized utility hub [73]. On the other hand, Maali (2009) developed a simple linear programming model to solve for a cooperative game. Their model is capable of reporting a Pareto optimal solution [76]. Later, Tan *et al*. (2016) adopted the approach by Maali (2009) to develop an optimization model for a cooperative game in an EIP [126]. The model was illustrated on a palm-based biomass processing complex and sago-based biorefinery.

From the literature above, it is noted that there has not been any research to address MCDM for an integrated pulp and paper biorefinery. Thus, it is the objective of this work to formulate and solve the MCDM problem through mathematical optimization and game theory. Firstly, an optimization model is formulated which reports the overall economic payoff of the EIP. Next, the individual enterprise payoffs are analyzed through cooperative game strategy.

6.3. Problem Statement

An optimization model is proposed which synthesize an EIP scheme governed by mass and energy balances. The proposed EIP consists of ($c \in C$) enterprises, which are a dissolving pulp mill (DPM), furfural biorefinery (FUB), gasification plant (GAS) and combined heat and power (CHP). Biomass ($b \in B$) generated from DPM can be sent to potential enterprise c, to be converted to biofuel or bioproduct. Next, energy demand in the EIP is satisfied by either the CHP, purchased externally from the grid or a combination of both. In this work, economic payoff based on profitability of the EIP is considered. The problem lies in determining the optimal EIP scheme, where the individual economic payoff of each enterprise is satisfied. Game theory is proposed to analyze the influence of multiple decision makers on the EIP network developed. The proposed methodology is presented in the next section.

6.4. Methodology for Model Formulation

The following indices are considered; index b denotes biomass feed sent to potential enterprises c, index c denotes enterprises, k is the CHP technology options, which are specific to c = 4. Finally, index s is the steam pressure level generated from the CHP. Besides, variables E and F represent electricity and flow rate, respectively (where $E \geq 0$, $F \geq 0$). It is assumed that the transmission of electricity (i.e. generated or consumed) is set at the same voltage. The parameter Y is the conversion factor, which dictates how much output is produced per unit of input.

6.4.1. Mass Balance

In dissolving pulp mill (DPM), wood chips (F^{CHIP}) are processed into pulp (F^{PULP}) at a conversion of Y^{PULP} as shown in Eq (6.1).

$$F^{\text{PULP}} = F^{\text{CHIP}}\text{Y}^{\text{PULP}} \qquad (6.1)$$

Besides, different biomass b is produced in DPM, denoted by F_b^{BIO} at a conversion of Y_b^{BIO}, as described in Eq (6.2). The allocation of biomass b from DPM to each potential enterprise c at a flow rate of F_{bc}^{BIOS} is denoted in Eq (6.3).

$$F_b^{\text{BIO}} = F^{\text{CHIP}}\text{Y}_b^{\text{BIO}} \qquad \forall b \qquad (6.2)$$

$$F_b^{\text{BIO}} = \sum_{c=1}^{C} F_{bc}^{\text{BIOS}} \qquad \forall b \qquad (6.3)$$

In the furfural biorefinery (FUB), furfural (F^{FUB}) is produced from biomass b (F_{bc}^{BIOS}), at a conversion of Y_b^{FUB}, as shown in (4).

$$F^{\text{FUB}} = \sum_{b=1}^{B} F_{bc}^{\text{BIOS}}\text{Y}_b^{\text{FUB}} \qquad (6.4)$$

Biomass b can also be sent to a gasification plant (GAS) to generate syngas (F^{SYN}) at a conversion of Y_b^{SYN} in Eq (6.5). Next, syngas is allocated to each potential enterprise c, at a flow of F_c^{SYNS}, as shown in Eq (6.6).

$$F^{\text{SYN}} = \sum_{b=1}^{B} F_{bc}^{\text{BIOS}}\text{Y}_b^{\text{SYN}} \qquad (6.5)$$

$$F^{\mathrm{SYN}} = \sum_{c=1}^{C} F_c^{\mathrm{SYNS}} \qquad \forall c \qquad (6.6)$$

In CHP, energy is generated in the form of steam and electricity through different CHP technology k. Energy required by an enterprise is an energy sink, denoted by superscript 'SK'; while energy produced by an enterprise is as an energy source, denoted by superscript "SR". Energy flows are shown as 'dotted lines' in **Figure 6.1**. First, steam is produced ($F_s^{\text{SR-BOI}}$) in Eq (6.7) at a steam level of s from combustion in a recovery boiler (k = 1), at a conversion of $\mathrm{Y}_{bs}^{\text{SR-BOI}}$. $F_b^{\text{BIO-EXT}}$ denote the purchase of external biofuel to supplement the production of steam. Eq (6.8) expressed the steam produced ($F_s^{\text{SR-CC}}$) at a steam level of s from a combined cycle (k = 3), at a conversion of $\mathrm{Y}_s^{\text{SR-CC}}$.

For k = 1, $$F_s^{\text{SR-BOI}} = \sum_{b=1}^{B} (F_{bc}^{\text{BIOS}} + F_b^{\text{BIO-EXT}}) \mathrm{Y}_{bs}^{\text{SR-BOI}} \qquad \forall s \qquad (6.7)$$

For k = 3, $$F_s^{\text{SR-CC}} = F_c^{\text{SYNS}} \mathrm{Y}_s^{\text{SR-CC}} \qquad \forall s \qquad (6.8)$$

Steam produced from each CHP technology k is then expanded through steam turbines to satisfy the steam requirement of the other enterprises. The cascade of steam flow rate is performed for each steam level s as shown in Eq (6.9). In Eq (6.9), the net steam flow rate ($F_{k,s}^{\text{CA}}$) at level s is cascaded from an earlier level s – 1 ($F_{s\text{-}1}^{\text{CA}}$) and from the net flow rate balance of steam *sources* ($F_{k,s}^{\text{SR}}$) and steam *sinks* ($F_{k,s}^{\text{SK}}$) at level s [127].

$$F_{k,s}^{\text{CA}} = F_{k,s-1}^{\text{CA}} + (F_{k,s}^{\text{SR}} - F_{k,s}^{\text{SK}}) \qquad \forall k \ \forall s \ (6.9)$$

The expansion of steam through the steam turbine generates power in (6.10). For each steam interval, power generated is the product of $F_{k,s\text{-}1}^{\text{CA}}$, turbine efficiency η and the difference in enthalpy between two steam levels (H_s) [127].

$$E_k^{\text{COGEN}} = \sum_{s=1}^{S} \eta F_{k,s-1}^{\text{CA}} (\mathrm{H}_{s-1} - \mathrm{H}_s) \qquad \forall k \qquad (6.10)$$

Besides, power could also be generated other than through the steam turbine. This additional power E_k^{CHP} is denoted in (6.11). In a combined cycle plant, power is generated from the gas turbine, denoted by $E^{\text{CHP-CC}}$, at a conversion of $\mathrm{Y}^{\text{EL-CC}}$.

For $k = 3$, $E^{\text{CHP-CC}} = F_c^{\text{SYNS}} \Upsilon^{\text{EL-CC}}$ (6.11)

The total power generation for each CHP technology k is denoted below in Eq (6.12).

$$E_k^{\text{SR}} = E_k^{\text{CHP}} + E_k^{\text{COGEN}} \qquad \forall k \qquad (6.12)$$

6.4.2. Energy Balance

Steam consumption at each steam level k, for each enterprise c is shown in Eq (6.13). This is the product of F_c^{INPUT} and the conversion factor of $\Upsilon_{c,s}^{\text{SK}}$. Note F_c^{INPUT} refers to the primary input of each enterprise c (e.g. F^{CHIP} for DPM)

$$\sum_{k=1}^{K} F_{k,s}^{\text{SK}} = \sum_{c=1}^{C} F_c^{\text{INPUT}} \Upsilon_{c,s}^{\text{SK}} \qquad \forall k \qquad (6.13)$$

Power demand in each enterprise c can also be denoted by a generic formulation as in Eq (6.14), where Υ_c^{EL} is the conversion factor to power for each enterprise c.

$$E_c^{\text{SK}} = F_c^{\text{INPUT}} \Upsilon_c^{\text{EL}} \qquad \forall c$$

(6.14)

Power demand in each enterprise c is then satisfied from the CHP at technology k (E_{kc}^{SK}), or purchased from the grid (E_c^{EXT}).

$$E_c^{\text{SK}} = \sum_{k=1}^{K} E_{kc}^{\text{SK}} + E_c^{\text{EXT}} \qquad \forall c \qquad (6.15)$$

Power generated from CHP for each technology k is shown below. E_k^{EXP} denote the export of excess power to the grid.

$$E_k^{\text{SR}} = \sum_{c=1}^{C} E_{kc}^{\text{SK}} + E_k^{\text{EXP}} \qquad \forall k \qquad (6.16)$$

An energy balance for power can be summarized using E^{CON}, E^{GEN}, E^{EXP} and E^{EXT} to denote the total power consumed, generated from CHP, exported to grid and purchased from grid, respectively.

If $E^{\text{CON}} - E^{\text{GEN}} > 0$; $E^{\text{CON}} = E^{\text{GEN}} + E^{\text{EXT}}$ (6.17)

If $E^{\mathrm{CON}} - E^{\mathrm{GEN}} \leq 0$; $\quad E^{\mathrm{CON}} = E^{\mathrm{GEN}} - E^{\mathrm{EXP}}$ (6.18)

where

$$E^{\mathrm{GEN}} = \sum_{k=1}^{K} E_k^{\mathrm{SR}} \tag{6.19}$$

$$E^{\mathrm{EXP}} = \sum_{k=1}^{K} E_k^{\mathrm{EXP}} \tag{6.20}$$

$$E^{\mathrm{CON}} = \sum_{c=1}^{C} E_c^{\mathrm{SK}} \tag{6.21}$$

$$E^{\mathrm{EXT}} = \sum_{c=1}^{C} E_c^{\mathrm{EXT}} \tag{6.22}$$

6.4.3. Economic Payoff

The total capital investment (TCI_c^{A}) of each enterprise c at an output capacity of F_c^{A} is estimated by the *sixth-tenths-factor* rule in Eq (6.23). The variables TCI_c^{B} denotes the total capital investment of enterprise j at output capacity F_c^{B}.

$$TCI_c^{\mathrm{A}} = TCI_c^{\mathrm{B}} \left(F_c^{\mathrm{A}} / F_c^{\mathrm{B}} \right)^{0.6} \qquad \forall c \tag{6.23}$$

Next, the annualized capital investment (ACI_c) is shown in Eq (6.24), where CR is the capital recovery factor at an interest loan of x and plant life of y.

$$ACI_c = \mathrm{CR}(TCI_c^{\mathrm{A}}) \qquad \forall c \tag{6.24}$$

$$\mathrm{CR} = \frac{x(1+x)^y}{(1+x)^y - 1} \tag{6.25}$$

The profitability of each enterprise c (GP_c) in the EIP is shown in Eq (6.26), where REV_c, $COST_c$ and AOT denote revenue, cost and annual operating time, respectively.

$$GP_c = (REV_c - COST_c)\mathrm{AOT} - ACI_c \qquad \forall c \tag{6.26}$$

Revenues are generated from the sale of product and/or waste from each enterprise c. Variables F_c^{P} and F_c^{W} denote flow rate of product and waste, while parameters $\mathrm{S}_c^{\mathrm{P}}$ and $\mathrm{S}_c^{\mathrm{W}}$ are the selling price of product and waste, respectively.

$$REV_c = F_c^{\mathrm{P}} \mathrm{S}_c^{\mathrm{P}} + F_c^{\mathrm{W}} \mathrm{S}_c^{\mathrm{W}} \qquad \forall c \qquad (6.27)$$

The cost incurred in each enterprise c ($COST_c$) consists of the purchase of raw materials and energy. Variables F_c^{R} and F_c^{U} denote consumption of raw materials and utilities in enterprise c. The parameters $\mathrm{S}_c^{\mathrm{R}}$ and $\mathrm{S}_c^{\mathrm{U}}$ are the selling price of raw material and utilities, respectively.

$$COST_c = F_c^{\mathrm{R}} \mathrm{S}_c^{\mathrm{R}} + F_c^{\mathrm{U}} \mathrm{S}_c^{\mathrm{U}} \qquad \forall c \qquad (6.28)$$

The overall annualized profit of the EIP is denoted as:

$$GP^{\mathrm{T}} = \sum_{c=1}^{C} GP_c \qquad (6.29)$$

6.5. Case Study

A hypothetical EIP case study based on a PPM biorefinery complex is used to illustrate the proposed approach, as shown in **Figure 6.1**. The enterprises considered include a dissolving pulp mill (c = 1), furfural biorefinery (c = 2), gasification plant (c = 3) and combined heat and power plant (c = 4). In dissolving pulp mill (DPM), part of the hemicellulose, known as pre-hydrolyzate liquor is extracted from the wood chips and sent to furfural biorefinery (FUB) [113]. Meanwhile, black liquor produced from DPM is sent to gasification plant (GAS) to generate syngas or to combined heat and power plant (CHP) to generate steam and electricity. In GAS, syngas can also be sent to CHP. Three different technologies for CHP are introduced; combustion in the recovery boiler (CHPR), the hog boiler (CHPH) and a combined cycle plant fuelled by syngas (CHPC).

Each enterprise has its own heating and power demand in the EIP. Currently, power demand can be supplied externally or from CHP. In CHP, two steam levels are generated; very high pressure steam (VHPS) and high pressure steam (HPS). VHPS (s = 1) is generated from CHPC while HPS (s = 2) is generated from CHPR and CHPH. Next, steam consumption is limited to DPM and FUB. DPM utilizes medium (MPS) and low pressure steam (LPS) while FUB consumes LPS. Besides, it is assumed that the CHP is energy self-sufficient. In this work, DPM produces three different sources of biomass; pre-hydrolyzate liquor (b = 1), hog fuel (b = 2) and black liquor (b = 3). The current work limits pre-hydrolyzate liquor to FUB, hog fuel to CHPH and black liquor to either CHPR or GAS. The input wood chip (F^{CHIP}) into DPM is set at 4000 t/d (46.3 kg/s). All supplementary data are provided in **Tables A4.1 – A4.6** in **Appendix 4**.

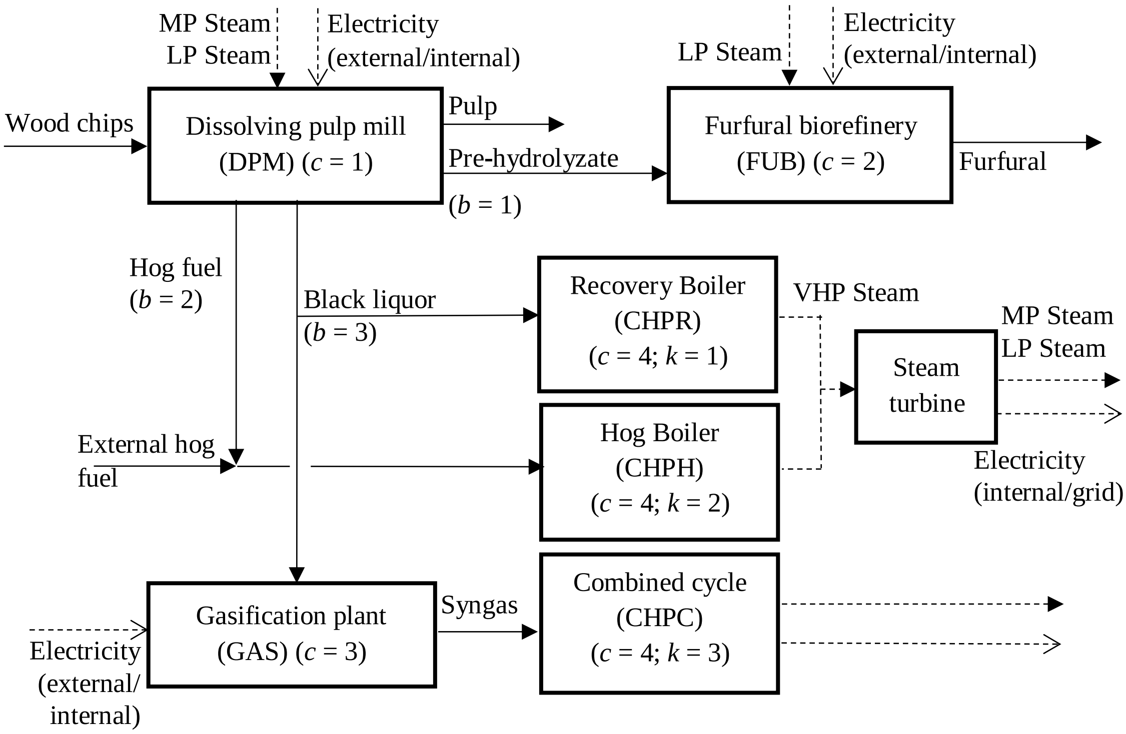


Figure 6.1. Proposed EIP with three different CHP technologies (CHPR, CHPH and CHPC)

In this work, the annual operating time (AOT) is taken as 330 d/y with a plant lifespan (y) of 20 years at a given interest rate (x) of 10% (**Table A4.5**, **Appendix 4**). Next, the reference base value of the total capital investment ($TCI^{B}{}_{c}$) and plant capacity ($F^{B}{}_{c}$) for each enterprise c is tabulated in **Table A4.6**. The model formulated is solved for the annualised profit GP^{T} Eq (6.29) subjected to equations Eq (6.1) – (6.28) using optimization software LINGO v13 [103]. The solver uses a branch-and-bound algorithm combined with linearization to obtain a global optimum solution for nonlinear models.

A global optimum solution is obtained at an overall annualised profit of USD 100.4 million. The distribution of revenue and costs for each enterprise in the EIP is tabulated in **Table 6.2**. The proposed EIP sent black liquor to GAS for syngas generation, which is fired in CHPC for heat and power production. At the same time, supplementary hog fuel is purchased and fired in CHPH to satisfy the overall heating demand in the EIP. The solution reported by the model indicated that the black liquor gasification (BLG) is favoured over conventional combustion, in agreement with the cited literature.

From **Table 6.2**, it is observed that there is an unequal distribution of individual profit among the enterprises, specifically CHPC with a negative net profit. From game theory perspective, viewing CHPC as a rational decision maker, it would not be interested in the proposed EIP initiative. Given that CHPC provides the bulk utility demand in the EIP, its withdrawal in participation would render the EIP unsuccessful. As such, each enterprise in the EIP would need to coordinate their strategy and redistribute their profit through cooperative game strategy.

Table 6.2. Distribution of revenue and costs of each enterprise in EIP

Enterprise	TCI^{A}_{c} **(USD million)**	ACI_c **(USD million/y)**	REV_c **(USD million/y)**	$COST_c$ **(USD million/y)**	GP_c **(USD million/y)**
DPM	891.0	104.7	481.0	333.7	42.6
FUB	43.8	5.1	40.8	5.0	30.7
GAS	160.0	18.8	129.7	87.3	23.6
CHPH	115.3	13.5	35.0	10.1	11.3
CHPC	121.2	14.2	136.1	130.0	-7.8
Total (EIP)	1331.3	156.3	822.6	566.1	100.4

Scenario 1: Cooperative game strategy through profit redistribution

In this scenario, the price of steam being traded from CHPH and CHPC is varied to redistribute the cash flow among the enterprises. From **Figure 6.2**, the optimal solution reported by the model previously corresponded to a steam price of USD 6/t. By setting a higher steam price, it is noted that the profit and can be allocated from DPM to CHPH and CHPC. Note that the overall total profit for all steam prices does not change (USD 100.4 million/y). The profit of DPM is most sensitive to the price set by CHPH and CHPC, given its high demand throughout its process. At a steam price of USD 12/t and above, CHPC would report its first positive net profit.

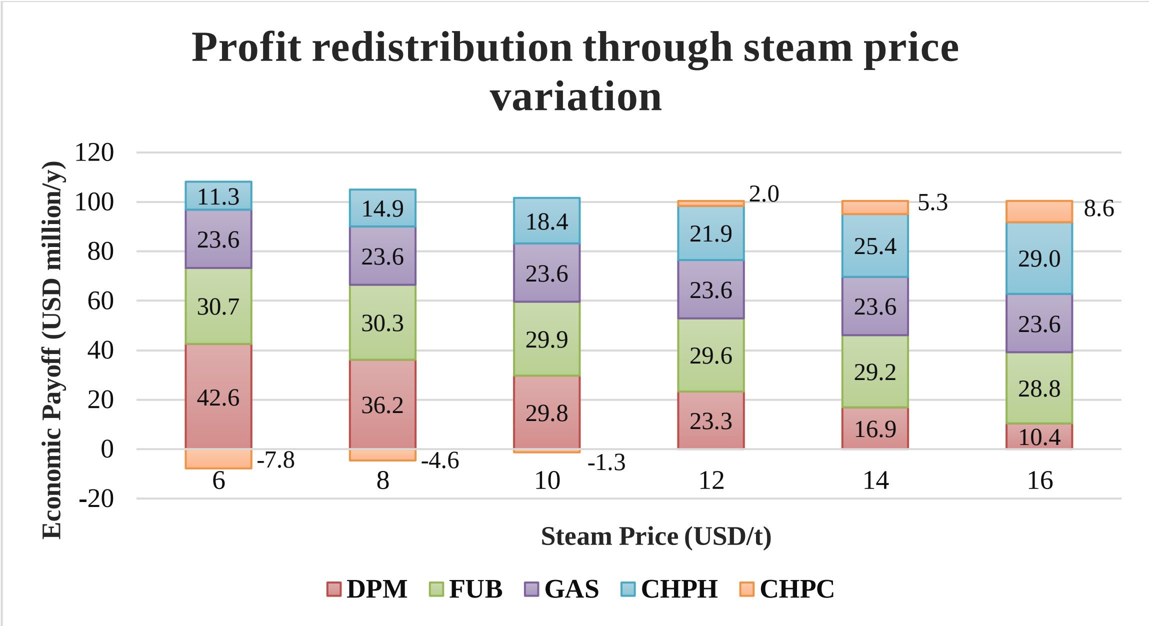


Figure 6.2. Profit redistribution through steam price variation

Scenario 2: Cooperative game strategy through uniform internal rate of return

In this scenario, the internal rate of return (IRR) of each enterprise *c* is determined. The IRR corresponds to a discount (or interest) rate at which the cumulative discounted cash flow, also known as the net present value (NPV_c) is zero. This method provides a robust evaluation of the profitability of a project by considering the required cash flow for each year of operation. A more profitable project would be able to afford to pay a higher IRR. Thus, in a cooperative game, the enterprises cooperate by varying the prices of steam and electricity. It is desired to determine whether a uniform IRR can be found.

First, the projected annual cash flow of each enterprise *c* is determined. The total capital investment (TCI^{A}_{c}), revenue (REV_c) and cost ($COST_c$) for the end of each operating year *y* can be extracted from **Table 6.2**. Here, it is assumed that each enterprise *c* invest its entire capital in its first year (y = 1), with no revenue generated or operating cost incurred. Next, it is also assumed that the production of each enterprise is set at 70% and 85% of its maximum capacity in its second year (y = 2) and third year(y = 3), respectively. From the fourth year of operation onwards (y = 4), production is running at 100% capacity.

The net cash flow of each enterprise *c* (NCF^{B}_{c}) at the end of each year *y* (before tax) is determined in Eq (6.30).

$$NCF_c^{B} = REV_c - COST_c - TCI_c^{A} \qquad \forall c \qquad (6.30)$$

Following this, the net cash flow of each enterprise c (NCF^{A}_{c}) after taxation is determined. First, the tax depreciation allowance (TD_c) is determined. As defined by Brennan (1998), it is an allowable deduction from the net cash flow before tax (NCF^{B}_{c}). It is expressed as a percentage of total capital investment (TCI^{A}_{c}), as shown in Eq (6.31), where k^{TD} is 5% [128].

$$TD_c = k^{TD} TCI_c^{A} \qquad \forall c \qquad (6.31)$$

Next, the taxable income (TI_c) of each enterprise c at the end of each year y is calculated in Eq (6.32) below.

$$TI_c = NCF_c^{B} - TD_c \qquad \forall c \qquad (6.32)$$

The amount of tax payable (TP_c) by each enterprise c at the end of each year y can then be determined in Eq (6.33). Here, a corporate tax rate (k^{TR}) of 30% is set.

$$TP_c = k^{TR} TI_c \qquad \forall c \qquad (6.33)$$

Next, the net cash flow of each enterprise c (NCF^{A}_{c}) at the end of each year y (after tax) is determined in Eq (6.34).

$$NCF_c^{A} = NCF_c^{B} - TP_c \qquad \forall c \qquad (6.34)$$

After this, the time value of money is taken into consideration by discounting the annual net cash flow (NCF^{A}_{c}) with the discount factor (DF) to obtain the discounted cash flow (DCF_c) for each year y. The expression for DCF_c and DF is shown in Eq (6.35) and Eq (6.36), where x is the initial discount rate and y is the operating year.

$$DCF_c = DF(NCF_c^{A}) \qquad \forall c \qquad (6.35)$$

$$DF = \frac{1}{(1+x)^{y}} \qquad \forall c \qquad (6.36)$$

The cumulative discounted cash flow (NPV_c) is expressed in Eq (6.37).

$$NPV_c = \sum DCF_c \qquad \forall c \qquad (6.37)$$

Table 6.3. Projected annual cash flow of DPM at a discount rate (x) of 10%

End of year (y)	Total capital investment, TCI^{A}_{c} (USD million)	Revenue, REV_c (USD million)	Cost, $COST_c$ (USD million)	Net cash flow before tax, NCF^{B}_{c} (USD million)	Tax depreciation, TD_c (USD million)	Taxable income, TI_c (USD million)	Tax payment, TP_c (USD million)	Net cash flow after tax, NCF^{A}_{c} (USD million)	Discount factor, DF	Discounted cash flow, DCF_c (USD million)	Cumulative discounted cash flow, NPV_c (USD million)
1	891	0	0	-891	0	0	0	-891	0.91	-810.0	-810.0
2	0	336.6	233.6	103.0	44.6	58.6	17.6	85.5	0.83	70.7	-739.3
3	0	408.8	283.6	125.2	44.6	80.6	24.2	101	0.75	75.8	-663.4
4	0	481.0	333.7	147.3	44.6	102.7	30.8	116.5	0.68	79.6	-583.9
5	0	481.0	333.7	147.3	44.6	102.7	30.8	116.5	0.62	72.3	-511.6
6	0	481.0	333.7	147.3	44.6	102.7	30.8	116.5	0.56	65.7	-445.8
7	0	481.0	333.7	147.3	44.6	102.7	30.8	116.5	0.51	59.8	-386.1
8	0	481.0	333.7	147.3	44.6	102.7	30.8	116.5	0.47	54.3	-331.7
9	0	481.0	333.7	147.3	44.6	102.7	30.8	116.5	0.42	49.4	-282.3
10	0	481.0	333.7	147.3	44.6	102.7	30.8	116.5	0.39	44.9	-237.4
11	0	481.0	333.7	147.3	44.6	102.7	30.8	116.5	0.35	40.8	-196.6
12	0	481.0	333.7	147.3	44.6	102.7	30.8	116.5	0.32	37.1	-159.5
13	0	481.0	333.7	147.3	44.6	102.7	30.8	116.5	0.29	33.7	-125.8
14	0	481.0	333.7	147.3	44.6	102.7	30.8	116.5	0.26	30.7	-95.1
15	0	481.0	333.7	147.3	44.6	102.7	30.8	116.5	0.24	27.9	-67.2
16	0	481.0	333.7	147.3	44.6	102.7	30.8	116.5	0.22	25.4	-41.9

17	0	481.0	333.7	147.3	44.6	102.7	30.8	116.5	0.20	23.0	-18.8
18	0	481.0	333.7	147.3	44.6	102.7	30.8	116.5	0.18	21.0	2.1
19	0	481.0	333.7	147.3	44.6	102.7	30.8	116.5	0.16	19.0	21.2
20	0	481.0	333.7	147.3	44.6	102.7	30.8	116.5	0.15	17.3	38.5
21	0	481.0	333.7	147.3	44.6	102.7	30.8	116.5	0.14	15.7	54.2

The IRR is determined by iteration or trial and error by adjusting the discount rate *x* until NPV_c reaches zero. **Table 6.3** illustrate an example of the projected annual cash flow for DPM in the proposed EIP, at an initial discount rate (*x*) of 10%. Through iteration, it can be determined that at a discount rate of approximately 10.9%, the NPV_c for DPM is zero (**Table 6.4**). The IRR for DPM is then reported as 10.9%. A similar calculation procedure is repeated for the other enterprises, and the results are tabulated in **Appendix 4** (**Table A4.7 – A4.10).**

Table 6.4. Comparison of annual cash flow for DPM at an initial discount rate of 10% and at an internal rate of return (IRR) of 10.9%

End of year (*y*)	**At discount rate (*x*) of 10%**			**At internal rate of return (IRR) of 10.9%**		
	Discount factor, *DF*	**Discounted cash flow, DCF_c (USD million)**	**Cumulative discounted cash flow, NPV_c (USD million)**	**Discount factor, *DF***	**Discounted cash flow, DCF_c (USD million)**	**Cumulative discounted cash flow, NPV_c (USD million)**
1	0.91	-810.0	-810.0	0.90	-803.2	-803.2
2	0.83	70.7	-739.3	0.81	69.5	-733.7
3	0.75	75.8	-663.4	0.73	74.0	-659.7
4	0.68	79.6	-583.9	0.66	76.9	-582.8
5	0.62	72.3	-511.6	0.60	69.3	-513.5
6	0.56	65.7	-445.8	0.54	62.5	-451.0
7	0.51	59.8	-386.1	0.48	56.3	-394.7
8	0.47	54.3	-331.7	0.44	50.8	-343.9
9	0.42	49.4	-282.3	0.39	45.8	-298.1
10	0.39	44.9	-237.4	0.35	41.3	-256.8
11	0.35	40.8	-196.6	0.32	37.2	-219.7
12	0.32	37.1	-159.5	0.29	33.5	-186.1
13	0.29	33.7	-125.8	0.26	30.2	-155.9
14	0.26	30.7	-95.1	0.23	27.2	-128.7
15	0.24	27.9	-67.2	0.21	24.6	-104.1
16	0.22	25.4	-41.9	0.19	22.1	-82.0
17	0.20	23.0	-18.8	0.17	20.0	-62.0
18	0.18	21.0	2.1	0.15	18.0	-44.0
19	0.16	19.0	21.2	0.14	16.2	-27.8
20	0.15	17.3	38.5	0.13	14.6	-13.2
21	0.14	15.7	54.2	0.11	13.2	0.00

Once the IRR of each enterprise *c* has been determined, the steam prices is then varied. As the steam price is varied, the revenue (REV_c) and cost ($COST_c$) among the enterprises would differ and be redistributed among the enterprises. Thus, the IRR of each enterprise *c* would need to be recalculated. It is then desired to investigate whether a uniform IRR for all enterprises in the EIP can be achieved. **Table 6.5** tabulates the IRR for each enterprise as steam prices are varied from USD 6/t to USD 12/t. At the initial LPS price of USD 6/t, it is seen that the IRR for CHPC is only 0.2%, indicating poor profitability, which correlated with the findings in **Scenario 1**. However, as steam prices increased to USD 12/t, the IRR for DPM with CHPC and GAS with CHPH reached a more uniform rate. Nonetheless, there is still a discrepancy in IRR between FUB and the other enterprises. The high IRR of FUB is attributed to the low TCI and operating cost of its process and high revenue from the furfural market. IRR of GAS remains unchanged as it is assumed no steam is consumed in the process.

Table 6.5. Negotiation of steam prices and its impact on IRR in cooperative game

Price of LPS (USD/t)	**IRR of each enterprise (%)**				
	DPM	**FUB**	**GAS**	**CHPH**	**CHPC**
6 (initial)	10.9	51.1	18.1	14.7	0.2
8	10.4	50.6	18.1	16.8	3.3
10	9.8	50.1	18.1	18.9	6.0
12	9.2	49.6	18.1	20.9	8.4

Next, the price of internal electricity being supplied by the CHPH and CHPC to the other enterprises are evaluated, as shown in **Table 6.6** (at a fixed LPS price of USD 6/t). The default electricity charged was set at USD 0.12/kWh. Given that DPM, FUB and GAS consumes electricity, it is observed that the IRR decreases as electricity prices increased. More importantly, the IRR of CHPC is increased significantly, owing to its high power-to-heat ratio, which generates more useful power over steam. From **Table 6.6**, it can be concluded the optimal solution for the enterprises lies at an electricity pricing of USD 0.14/kWh. At this price, the IRR of GAS, CHPH and CHPC lies in the range of 14.5 – 17.2%. At the same time, the IRR of DPM remains acceptable in the range of 9.3 – 10.1%. It is seen that a uniform IRR among all enterprises is difficult to be achieved. The reason for this is that the DPM is sensitive to the prices of steam and electricity, given the high demand in its processes. FUB on the other is robust to these changes as the low initial TCI and high revenue compensates for the cost of steam and electricity.

Table 6.6. Negotiation of electricity prices and its impact on IRR in cooperative game

Price of electricity (USD/kWh)	IRR of each enterprise (%)				
	DPM	**FUB**	**GAS**	**CHPH**	**CHPC**
0.12 (initial)	10.9	51.1	18.1	14.7	0.2
0.13	10.1	50.9	17.1	14.9	8.3
0.14	9.3	50.8	16.1	17.2	14.5
0.15	8.4	50.6	15.1	18.4	20.0

From evaluation of IRR in **Table 6.7**, there is still a large discrepancy in the reported IRR between DPM and FUB. Given the main commodity traded is pre-hydrolyzate, DPM and FUB could renegotiate the price of pre-hydrolyzate to reach a comparable IRR among all participating enterprise in the EIP. The results are tabulated in **Table 6.7**; which indicates a high selling price of pre-hydrolyzate (USD 600/t) is required to reach a uniform IRR between DPM and FUB.

Table 6.7. Negotiation of pre-hydrolyzate prices and its impact on IRR in cooperative game

Price of pre-hydrolyzate (USD/t)	IRR of each enterprise (%)	
	DPM	**FUB**
0	9.0	53.9
50 (initial)	9.3	50.8
200	9.9	41.2
400	10.8	27.8
550	11.5	17.0
600	11.7	13.0

6.6. Conclusion

An optimization model is developed for an EIP using a DPM as an anchor enterprise. The model reported an optimal solution with an overall annual profit of USD 100.4 million. However, the individual profit of each enterprise varied greatly from the optimization solution. Cooperative game strategy was introduced, where enterprises coordinate together to reallocate their profit and cost, using the optimal solution from the model as a benchmark. The first cooperative game scenario examines the change in individual profit as the price of commodity being traded is varied. The second cooperative game scenario seeks to determine a uniform IRR among each enterprise. In summary, a price of USD 6/t, USD 0.14/kWh and USD 600/t for steam, electricity and pre-hydrolyzate, respectively, the IRR for all enterprises achieve a minimum IRR of 10%. The IRR method provides a robust and detailed evaluation of the profitability of an EIP project. This ensures all enterprise remain profitable to ensure the continuing involvement of the CHP, which provides the bulk of utility in the EIP.

Future work could incorporate detailed environmental payoff of each enterprise into the methodology. For instance, life cycle assessment can be used to determine specific emissions across each enterprise in the EIP. This encourages further cooperation as there is a need to balance the payoff between economic and environmental aspects. Next, a dynamic game strategy could also be studied, where enterprises reviewed their strategies periodically and adjust the optimal outcome accordingly.

Chapter 7: Conclusion and Future Works

In this research project, a sustainable integrated pulp and paper biorefinery (IPPB) was synthesized using mathematical optimization techniques. Concurrently, a strategic decision making (SDM) framework was introduced in the IPPB to resolve the multiple-criteria decision making (MCDM) problem. Firstly, the research project (**Chapter 3**) formulated an optimization model for an IPPB, which optimized for the material, water, energy and profitability of an IPPB. It was found that simultaneous water and energy optimization in an IPPB is critical, as it directly affects the quantity and quality of black liquor. By optimizing the IPPB as a whole, the mathematical model was able to report the most profitable biorefinery pathway for black liquor in an IPPB.

Later, the next stage of the research project (**Chapter 4**) synthesized an EIP network with consideration of both economic and environmental performance. A quantitative index termed, eco-connectance (C^{E}) relates the level of connectivity in an EIP (which quantifies the environmental performance). The index above is embedded along with the economic performance of the EIP into the mathematical model. Payback period is used as an assessment of the economic performance. It is concluded that with an increase in the number of industry participation in an EIP, the eco-connectance increases. However, this would require a substantial amount of capital expenditure, resulting in a longer payback period for the EIP to generate a positive economic performance. Thus, although a high eco-connectance is desired to maximise the exchange of waste and by-product, the initial capital expenditure of introducing multiple industries might hinder the beneficial exchange of waste and by-product.

Following this, the MCDM problem in the IPPB is addressed in **Chapter 5 and 6**. A SDM framework incorporating three different game models was implemented. The game models considered are non-cooperative game, cooperative game to Stackelberg game. These game models will reveal whether a mutually agreeable and sustainable EIP scheme can be achieved. The developed methodology was applied in an EIP case study using a KPM as the anchor enterprise. It was found that cooperative behaviour among enterprises could improve the overall economic and environmental payoff across the EIP. However, it is paramount that the payoffs among enterprises are equitable and fair. Thus, the Stackelberg game model was found to be insightful by introducing an EIP authority with the position of power. Through carbon abatement and taxation scheme, all enterprises across the EIP could be sustainable and stable.

Next, future direction of the research project could incorporate social payoff into the SDM framework. This would add an additional layer of complexity and realism into the EIP initiative. For instance, social payoff include the potential for job creation from the EIP initiative, leading to increased regional development. Besides, the interests of the local residents could be considered as a third party in the decision making process. This could be beneficial to ensure the long term viability of the EIP initiative. Moving on, the research project highlighted the importance of an anchor enterprise towards the successful implementation of an EIP. Given its ability to form multiple industrial symbiotic networks, it is paramount that future EIP initiative considers the major contribution by an anchor enterprise. As the anchor enterprise is responsible for the conversion of biomass into biofuel and bioproduct, the EIP authority would need to implement incentives or rewards to compensate it. This include reduced corporate taxation or feed-in tariff policies to encourage continuous participation.

Besides, other areas of studies include the incorporation of dynamic game strategy into the EIP. Currently, the research project deals with a static game model, where the final decision from the SDM framework is fixed. In dynamic game strategy however, enterprises in an EIP could reviewed their strategies periodically (e.g. every 3 – 6 months or annually) and adjust the optimal EIP scheme accordingly. For instance, fluctuations in crude oil prices may result in a situation where the utilization of biomass as fuel source may not be economically viable. Instead, it may be beneficial for the biomass to be processed into specialty chemical. On the other hand, as renewable energy technologies become increasingly competitive, certain enterprises may withdraw from the EIP while other enterprises may wish to join the EIP if it is beneficial to them. Thus, a dynamic game model could provide insight on the long term viability of the EIP.

Nomenclature

Acronyms

BIO	bioethanol refinery
BL	black liquor
BLG	black liquor gasification
BLGCC	black liquor gasification combined cycle
BLGMF	black liquor gasification with motor fuel production
BSWS	brown stock washing system
CCS	carbon capture and storage
CHP	combined heat and power plant
CHPC	combined cycle
CHPH	combustion in hog boiler
CHPR	combustion in recovery boiler
CUB	centralized utility hub
DCF	discounted cash flow
DME	dimethyl ether fuel
DPM	dissolving pulp mill
DR	displacement ratio
DS	dissolved solids
EIP	eco-industrial park
EMCC	extended modified continuous cooker
FAHP	fuzzy analytic hierarchy process
FT	fischer-tropsch fuel
FUB	furfural biorefinery
GAS	gasification plant
GIFBR	green integrated forest biorefinery
GP	gross profit
HPS	high pressure steam
IGCC	integrated gasification combined cycle
IPPB	integrated pulp and paper biorefinery
IPWI	interplant water integration
IRR	internal rate of return
IS	industrial symbiosis

KPM	Kraft pulp mill
LP	linear programming
LPS	low pressure steam
MA	mixed-alcohol fuel
MCDM	multiple criteria decision making
MEE	multiple-effect evaporator
MILP	mixed-integer linear programming
MINLP	mixed-integer non-linear programming
MPS	medium pressure steam
NLP	non-linear programming
NPE	non-process elements
NPV	net present value
PH/PHL	pre-hydrolyzate liquor
PPM	pulp and paper mill
PSE	process systems engineering
RCN	resource conservation network
SBL	strong black liquor
SDM	strategic decision making
SNG	synthetic natural gas
TCI	total capital investment
TOM	Tomlinson/recovery boiler
TRP	twin roll press
VHPS	very high pressure steam
WBL	weak black liquor

Sets

b	index for biomass (Chapter 3 – 4, 6)
c	index for enterprise or bioenergy industry or bio-product industry (Chapter 4 – 6)
d	index for steam header (Chapter 4)
e	index for electricity (Chapter 3)
f	index for by-product sink (Chapter 4)
g	index for steam sink (Chapter 4)
h	index for EIP scheme (Chapter 5)
i	index for washer (Chapter 3)
j	index for subsequent washer, $i + 1$ (Chapter 3)
k	index for pathway conversion from biomass into intermediate (Chapter 3)
k'	index for pathway conversion from intermediate into final product (Chapter 3)
l	index for intermediate (Chapter 3)
l'	index for final product (Chapter 3)
p	indx for output product (Chapter 5)
q	index for input raw material and/or utility (Chapter 5)
r	index for CO_2 emission source (Chapter 5)
s	index for steam (Chapter 3 and 6)

Parameters

$\overline{H}$	average specific enthalpy of black liquor in multiple-effect evaporator
a	efficiency of the multiple-effect evaporator
AF	annualized factor
AOT	annual operating time
a^w	cost constant for washer
b^w	cost constant for washer
C_p	unit selling cost of product *p*
C_P^{OR}	heat capacity for pulp mat in oxygen delignification reactor
C_q	unit purchase cost of raw material and/or utility *q*
CR	capital recovery factor
DR_i	displacement ratio of washer *i*
EF_r	CO_2 emission factor from emission source *r*
F_i^D	pulp inlet flow rate of washer *i*
F_i^F	filtrate flow rate out of washer *i*
F_i^P	pulp outlet flow rate of washer *i*
F_i^S	shower flow rate into washer *i*
H_{s-1}	enthalpy of steam pressure *s*
I^w	number of washers
k^{TD}	tax depreciation as a percentage of total capital investment TCI^A_c
k^{TR}	corporate tax rate
η	steam turbine efficiency
OH	operating hour (d/y)
P_e^{ELEC}	selling price of exported electricity to grid
P^{FW}	cost of freshwater consumption in BSWS
P_{kl}	processing cost of intermediate *l* via pathway *kl*
$P_{k'l'}$	processing cost of product *l'* via pathway *k'l'*
$P_{l'}^{PROD}$	selling price of biorefinery products
P^Q	cost of energy consumption in BSWS
PR	pulp production rate (ton of pulp/d)
P_s^{LP}	selling price of low pressure steam
P_s^{MP}	selling price of medium pressure steam
S_c^P	unit selling price of product in enterprise *c*

S_c^{R}	unit purchase price of raw material in enterprise *c*
S_c^{U}	unit purchase price of utilities in enterprise *c*
S_c^{W}	unit selling price of waste in enterprise *c*
S^{n}	size parameter for washer
t^{OH}	operating hour (h/y)
t^{OT}	operating time (s/h)
x	interest rate
X_{bc}^{CAPEX}	capital investment cost parameter for each industry *c*
X^{BP}	selling cost parameters for by-product
$X^{BP\text{-}EXP}$	selling cost parameters for product (exported)
$X^{BP\text{-}IMP}$	purchase cost parameter for imported by-product
X_c^{P}	selling cost parameters for product
X_d^{PS}	selling cost parameters for steam header *d* (within EIP)
$X_d^{PS\text{-}EXP}$	selling cost parameters for steam header *d* (exported)
$X_d^{PS\text{-}IMP}$	purchase cost parameter for steam header *d*
y	number of operating years
Y_b^{BIO}	conversion factor of wood chip to biomass *b*
Y_{bc}^{BP}	conversion factor of biomass *b* to by-product in industry *c*
Y_{bcd}^{PS}	conversion factor of biomass *b* to steam header *d* in industry *c*
Y_{bc}^{P}	conversion factor of biomass *b* to product in industry *c*
Y_b^{FUB}	conversion factor of biomass *b* to furfural
$Y_{bs}^{SR\text{-}BOI}$	conversion factor of biomass *b* to steam in boiler at steam pressure *s*
Y_b^{SYN}	conversion factor of biomass *b* to syngas
$Y_{c,s}^{SK}$	conversion factor of steam consumption in enterprise *c*
Y_c^{EL}	conversion factor to power for each enterprise *c*
$Y^{EL\text{-}CC}$	conversion factor of biomass to power in combined cycle
Y_{ke}^{ELEC}	conversion of electricity per unit of biomass via pathway *k*
Y_{kl}	conversion of biomass into intermediate *l*
$Y_{k'l'}$	conversion of intermediate *l* into product *l'*
Y_{ks}^{LPST}	conversion of low pressure steam per unit biomass via pathway *k*
Y_{kss}^{MPST}	conversion of medium pressure steam per unit biomass via pathway *k*
Y_{le}^{ELEC}	conversion of electricity per unit of intermediate *l* via pathway *k'*
Y_{ls}^{LPST}	conversion of low pressure steam per unit of intermediate *l* via pathway *k'*
Y_{lss}^{MPST}	conversion of medium pressure steam per unit of intermediate *l* via pathway *k'*

Y^{PULP} conversion factor of wood chip to pulp

$Y_s^{SR\text{-}CC}$ conversion factor of biomass *b* to steam in combined cycle at steam pressure *s*

Variables

ACI_c	annualized capital investment for enterprise *c*
ADC_c	asymmetric distribution coefficient for enterprise *c* (Chapter 5)
C	connectance
$CAPEX$	capital investment of an EIP
C^{E}	eco-connectance
CF^{FW}	DS concentration of freshwater
CF_i^{D}	pulp inlet DS concentration in washer *i*
CF_i^{F}	filtrate outlet DS concentration in washer *i*
CF_i^{P}	pulp outlet DS concentration in washer *i*
CF_i^{RTD}	DS concentration of twin roll press filtrate being sent for reuse at dilution point of washer *i*
CF_i^{RTS}	DS concentration of twin roll press filtrate being sent for reuse at shower point of washer *i*
CF_i^{S}	shower inlet DS concentration in washer *i*
CF^{OR}	DS concentration of pulp stream leaving oxygen delignification reactor
CF^{TRPD}	DS concentration at dilution point of TRP
CF^{TRPF}	DS concentration at filtrate point of TRP
CF^{TRPO}	DS concentration at outlet point of TRP
CO_c	net CO_2 emission of enterprise *C* (Chapter 5)
$COST_c$	cost of enterprise *c*
DCF_c	discounted cash flow for enterprise *c* at the end of year *y*
DF	discount factor at the end of year *y*
E_c^{EXT}	external power demand in each enterprise *c*
$E^{CHP\text{-}CC}$	additional power generated from gas turbine
E^{CON}	total energy consumption in EIP (Chapter 6)
E_c^{SK}	power demand in each enterprise *c*
E^{EXP}	total excess energy in EIP (Chapter 6)
E^{EXT}	total external energy purchased in EIP (Chapter 6)
E^{GEN}	total energy generated in EIP (Chapter 6)
E_k^{CHP}	additional power generated from CHP technology *k*
E_k^{COGEN}	power generated from steam turbine
E_k^{EXP}	export of excess power from CHP technology *k*

E_k^{SR}	total power generated (Chapter 6)
F_b^{B}	total flow rate of biomass *b*
F_b^{BIO}	flow rate of biomass *b*
$F_b^{BIO\text{-}EXT}$	flow rate of externally purchased biomass *b*
F_{bc}^{B}	flow rate of biomass *b* to industry *c*
F_{bc}^{BIOS}	allocation of biomass *b* to enterprise *c*
$F_{bc}^{B\text{-}MIN}$	minimum biomass flow rate
F_c^{A}	flow rate of primary output in enterprise *c* at an output capacity A
F_c^{B}	flow rate of primary output in enterprise *c* at an output capacity B
F_c^{BP}	flow rate of by-product in industry *c*
$F_c^{BP\text{-}EXP}$	export of excess by-product from industry *c*
F_{cdg}^{PS}	allocation of steam header *d* from industry source *c* to steam sink *g*
F_{cd}^{PS}	flow rate of steam header *d* in industry *c*
$F_{cd}^{PS\text{-}EXP}$	export of excess steam header *d* from industry *c*
F_{cf}^{BP}	allocation of by-product from industry source *c* to industry sink *f*
$F_{cf}^{BP\text{-}MIN}$	minimum by-product flow rate
F^{CHIP}	flow rate of wood chip
F_c^{INPUT}	flow rate of primary input in enterprise *c*
F_c^{P}	flow rate of product in enterprise *c*
F_c^{P}	flow rate of product in industry *c*
F_{cp}	flow rate of product *p* for enterprise *c* (Chapter 5)
F_{cq}	flow rate of raw material and/or utility *q* for enterprise *c* (Chapter 5)
F_c^{R}	flow rate of raw material in enterprise *c*
F_{cr}	flow rate of process stream from emission source *r* for enterprise *c* (Chapter 5)
F_c^{SYNS}	allocation of syngas to enterprise *c*
F_c^{U}	flow rate of utilities in enterprise *c*
F_c^{W}	flow rate of waste in enterprise *c*
$F_{dg}^{PS\text{-}IMP}$	import of steam header *d* to steam sink *g*
F^{DSOR}	amount of lignin produced during the delignification process
F_e^{ELEC}	total generated electrical power
$F_f^{BP\text{-}SK}$	flow rate of by-product sink *f*
$F_f^{BP\text{-}IMP}$	import of by-product to industry sink *f*
F^{FUB}	flow rate of furfural
F^{FW}	total freshwater consumption

F^{FWT}	freshwater flow rate into twin roll press dilution press
F_i^{BL}	black liquor flow rate from washer *i*
F_i^{BLE}	black liquor flow rate sent to multiple-effect evaporator from washer *i*
F_i^{BLR}	black liquor flow rate from washer *i* sent back for recycle in EMCC
F_i^{FWD}	freshwater flow rate into dilution point of washer *i*
F_i^{FWS}	freshwater flow rate into shower point of washer *i*
F_{ij}^{RD}	filtrate of washer *i* being sent for reuse at dilution point of washer *j*
F_{ij}^{RS}	filtrate of washer *i* being sent for reuse at shower point of washer *j*
F_i^{RT}	filtrate of washer *i* being sent for reuse at twin roll press dilution point
F_i^{RTD}	twin roll press filtrate being sent for reuse at dilution point of washer *i*
F_i^{RTS}	twin roll press filtrate being sent for reuse at shower point of washer *i*
$F_{k,s}^{\mathrm{CA}}$	net steam flow rate at steam pressure *s* from CHP technology *k*
$F_{k,s}^{\mathrm{SK}}$	net flow rate balance of steam sinks at pressure *s* from CHP technology *k*
$F_{k,s}^{\mathrm{SR}}$	net flow rate balance of steam sources at pressure *s* from CHP technology *k*
F_k^{SBL}	flow rate of strong black liquor to pathway *k*
$F_{l'}^{\mathrm{PROD}}$	total production of product *l'*
F_l	total production of intermediate *l*
$F_{lk'}^{\mathrm{INT}}$	flow rate of intermediate *l* to pathway *k'*
F^{OR}	flow rate exiting oxygen delignification reactor
F^{PULP}	flow rate of pulp
F^{RTT}	self-recycled flow rate of TRP back to dilution point
$F_{s\text{-}1}^{\mathrm{CA}}$	cascade of steam flow rate
F^{SBL}	strong black liquor flow rate
F_s^{LPST}	total production of low pressure steam
F_s^{MPST}	total production of medium pressure steam
$F_s^{\mathrm{MPST\_BSWS}}$	amount of medium pressure steam supplied to BSWS from biorefinery
$F_s^{\mathrm{MPST\_EX}}$	total production of excess medium pressure steam
$F_s^{\mathrm{MPST\_PUR}}$	amount of externally purchased medium pressure steam
$F_s^{\mathrm{MPST\_REQ}}$	amount of medium pressure steam required by BSWS
$F_s^{\mathrm{SR\text{-}BOI}}$	source flow rate of steam from boiler at steam pressure *s*
$F_s^{\mathrm{SR\text{-}CC}}$	source flow rate of steam from combined cycle at steam pressure *s*
F^{SYN}	flow rate of syngas
F^{TRPD}	flow rate at dilution point of TRP
F^{TRPF}	flow rate at filtration point of TRP

F^{TRPO}	flow rate at outlet point of TRP
F^{V}	amount of moisture removed
F^{WASHER}	annualized washer cost
G^{BP}	revenue from by-product
G^{P}	revenue from product
GP_c	profitability of enterprise *c*
G^{PS}	revenue from steam
GP^{T}	total profitability of an EIP (Chapter 6)
L	number of linkages
L^{B}	number of linkages for biomass
L_{bc}^{B}	binary integer representing the biomass link
L^{BP}	number of linkages for by-product
L_{cf}^{BP}	binary integer representing the by-product link
L^{E}	number of linkages for by-product or waste flow
L^{P}	number of linkages for product flow
NCF^{A}_c	net cash flow of enterprise *c* at the end of year *y* (after tax)
NCF^{B}_c	net cash flow of enterprise *c* at the end of year *y* (before tax)
NPV_c	cumulative discounted cash flow for enterprise *c* (or the net present value)
PP	payback period of an EIP
$PROFIT$	profitability of an EIP
Q^{MEE}	heat requirement of multiple-effect evaporator
Q^{OR}	heat requirement of oxygen delignification reactor
Q^{TOT}	total heat requirement in BSWS
REV_c	revenue of enterprise *c*
RS_c	ratio of symbiosis profit to symbiosis cost for enterprise *c* (Chapter 5)
RS_h^{EIP}	ratio of symbiosis profit to symbiosis cost for EIP *h* (Chapter 5)
S	number of industries/enterprises
SC_c	symbiosis cost of enterprise *c* (Chapter 5)
SP_c	symbiosis profit of enterprise *c* (Chapter 5)
SR_c	symbiosis revenue of enterprise *c* (Chapter 5)
TCI_c^{A}	total capital investment of enterprise *c* at an output capacity A
TCI_c^{B}	total capital investment of enterprise *c* at an output capacity B
TD_c	tax depreciation allowance for enterprise *c* at the end of year *y*
TF^{FW}	temperature of freshwater

TF_i^{D} pulp stream temperature at pulp inlet of washer i

TF_i^{F} pulp stream temperature at filtrate of washer i

TF_i^{P} pulp stream temperature at pulp outlet of washer i

TF_i^{RTD} stream temperature of twin roll press filtrate being sent for reuse at dilution point of washer i

TF_i^{RTS} stream temperature of twin roll press filtrate being sent for reuse at shower point of washer i

TF_i^{S} pulp stream temperature at shower of washer i

TI_c taxable income for enterprise c at the end of year y

T^{OR} pulp stream temperature exiting oxygen delignification reactor

TP_c tax payable for enterprise c at the end of year y

T^{TRP} pulp stream temperature leaving TRP

π permutation or order (Chapter 5)

$\upsilon(P_c^{\pi} \cup c) - \upsilon(P_c^{\pi})$ marginal contribution of enterprise c in permutation π (Chapter 5)

$\phi_c(\upsilon)$ Shapley value of enterprise c (Chapter 5)

References

1. Brundtland, G.H., Khalid, M., Agnelli, S., S.A., A.-A., Chidzero, B., Fadika, L.M., Hauff, V., Lang, I., Shijun, M., Marino de Botero, M., Singh, N., Nogueira-Neto, P., Okita, S., Ramphal, S.S., Ruckelshaus, W.D., Sahnoun, M., Salim, E., Shaib, B., Sokolov, V., Stanovnik, J., Strong, M., and Macneill, J., *Our Common Future - The World Commission on Environment and Development*. 1987: Oxford, New York.
2. Azapagic, A. and Perdan, S., *Indicators of sustainable development for industry: A general framework.* Process Safety and Environmental Protection, 2000. **78**(4): p. 243-261.
3. Ness, B., Urbel-Piirsalu, E., Anderberg, S., and Olsson, L., *Categorising tools for sustainability assessment.* Ecological Economics, 2007. **60**(3): p. 498-508.
4. Herva, M., Franco, A., Carrasco, E.F., and Roca, E., *Review of corporate environmental indicators.* Journal of Cleaner Production, 2011. **19**(15): p. 1687-1699.
5. Moldan, B., Janoušková, S., and Hák, T., *How to understand and measure environmental sustainability: Indicators and targets.* Ecological Indicators, 2012. **17**: p. 4-13.
6. Herva, M. and Roca, E., *Review of combined approaches and multi-criteria analysis for corporate environmental evaluation.* Journal of Cleaner Production, 2013. **39**: p. 355-371.
7. Lowe, E.A., *Creating by-product resource exchanges: Strategies for eco-industrial parks.* Journal of Cleaner Production, 1997. **5**(1-2): p. 57-65.
8. Chertow, M.R., *"Uncovering" industrial symbiosis.* Journal of Industrial Ecology, 2007. **11**(1): p. 11-30.
9. Park, H.S., Rene, E.R., Choi, S.M., and Chiu, A.S.F., *Strategies for sustainable development of industrial park in Ulsan, South Korea-From spontaneous evolution to systematic expansion of industrial symbiosis.* Journal of Environmental Management, 2008. **87**(1): p. 1-13.
10. Lambert, A.J.D. and Boons, F.A., *Eco-industrial parks: Stimulating sustainable development in mixed industrial parks.* Technovation, 2002. **22**(8): p. 471-484.
11. Tian, J., Liu, W., Lai, B., Li, X., and Chen, L., *Study of the performance of eco-industrial park development in China.* Journal of Cleaner Production, 2014. **64**: p. 486-494.

12. Jung, S., Dodbiba, G., Chae, S.H., and Fujita, T., *A novel approach for evaluating the performance of eco-industrial park pilot projects.* Journal of Cleaner Production, 2013. **39**: p. 50-59.

13. Taskhiri, M.S., Behera, S.K., Tan, R.R., and Park, H.S., *Fuzzy optimization of a waste-to-energy network system in an eco-industrial park.* Journal of Material Cycles and Waste Management, 2014.

14. Park, H.S. and Behera, S.K., *Methodological aspects of applying eco-efficiency indicators to industrial symbiosis networks.* Journal of Cleaner Production, 2014. **64**: p. 478-485.

15. Stephens, M., *Pulp & paper prospects in Australia: Looking to the future.* Appita Journal, 2013. **66**(1): p. 13-15.

16. Blanco, A., Negro, C., Monte, C., Fuente, E., and Tijero, J., *The challenges of sustainable papermaking.* Environmental Science and Technology, 2004. **38**(21): p. 414A-420A.

17. Biermann, C.J., *Chapter 3: Pulping Fundamentals*, in *Handbook of Pulping and Papermaking (Second Edition)*, C.J. Biermann, Editor. 1996, Academic Press: San Diego. p. 55-100.

18. Liu, S., Abrahamson, L.P., and Scott, G.M., *Biorefinery: Ensuring biomass as a sustainable renewable source of chemicals, materials, and energy.* Biomass and Bioenergy, 2012. **39**: p. 1-4.

19. Tay, D.H.S., Ng, D.K.S., Sammons, N.E., and Eden, M.R., *Fuzzy optimization approach for the synthesis of a sustainable integrated biorefinery.* Industrial and Engineering Chemistry Research, 2011. **50**(3): p. 1652-1665.

20. Gavrilescu, D., *Energy from biomass in pulp and paper mills.* Environmental Engineering and Management Journal, 2008. **7**(5): p. 537-546.

21. El-Halwagi, M.M., *Pollution Prevention through Process Integration: Systematic Design Tools*. 1997, San Diego, CA, USA: Academic Press.

22. Ng, D.K.S., Foo, D.C.Y., Tan, R.R., Pau, C.H., and Tan, Y.L., *Automated targeting for conventional and bilateral property-based resource conservation network.* Chemical Engineering Journal, 2009. **149**(1-3): p. 87-101.

23. Saw, S.Y., Lee, L., Lim, M.H., Foo, D.C.Y., Chew, I.M.L., Tan, R.R., and Klemeš, J.J., *An extended graphical targeting technique for direct reuse/recycle in concentration and property-based resource conservation networks.* Clean Technologies and Environmental Policy, 2011. **13**(2): p. 347-357.

24. Chen, C.L., Lee, J.Y., Ng, D.K.S., and Foo, D.C.Y., *Property integration for resource conservation network synthesis in palm oil mills.* Chemical Engineering Journal, 2011. **169**(1-3): p. 207-215.
25. Tan, Y.L., Ng, D.K.S., El-Halwagi, M.M., Foo, D.C.Y., and Samyudia, Y., *Synthesis of heat integrated resource conservation networks with varying operating parameters.* Industrial and Engineering Chemistry Research, 2013. **52**(22): p. 7196-7210.
26. Chew, I.M.L., Foo, D.C.Y., Ng, D.K.S., and Tan, R.R., *Flowrate targeting algorithm for interplant resource conservation network. Part 1: Unassisted integration scheme.* Industrial and Engineering Chemistry Research, 2010. **49**(14): p. 6439-6455.
27. Chew, I.M.L., Foo, D.C.Y., and Tan, R.R., *Flowrate targeting algorithm for interplant resource conservation network. Part 2: Assisted integration scheme.* Industrial and Engineering Chemistry Research, 2010. **49**(14): p. 6456-6468.
28. Chen, C.L., Lee, J.Y., Ng, D.K.S., and Foo, D.C.Y., *Synthesis of resource conservation network with sink-source interaction.* Clean Technologies and Environmental Policy, 2010. **12**(6): p. 613-625.
29. Kokossis, A.C. and Yang, A., *On the use of systems technologies and a systematic approach for the synthesis and the design of future biorefineries.* Computers and Chemical Engineering, 2010. **34**(9): p. 1397-1405.
30. Ng, R.T.L. and Ng, D.K.S., *Systematic approach for synthesis of integrated palm oil processing complex. Part 1: Single owner.* Industrial and Engineering Chemistry Research, 2013. **52**(30): p. 10206-10220.
31. Aviso, K.B., Tan, R.R., Culaba, A.B., and Cruz Jr, J.B., *Bi-level fuzzy optimization approach for water exchange in eco-industrial parks.* Process Safety and Environmental Protection, 2010. **88**(1): p. 31-40.
32. Aviso, K.B., Tan, R.R., Culaba, A.B., and Cruz Jr, J.B., *Fuzzy input-output model for optimizing eco-industrial supply chains under water footprint constraints.* Journal of Cleaner Production, 2011. **19**(2-3): p. 187-196.
33. Ng, R.T.L., Ng, D.K.S., and Tan, R.R., *Optimal planning, design and synthesis of symbiotic bioenergy parks.* Journal of Cleaner Production, 2015. **87**(1): p. 291-302.
34. Jacob, J., Kaipe, H., Couderc, F., and Paris, J., *Water network analysis in pulp and paper processes by pinch and linear programming techniques.* Chemical Engineering Communications, 2002. **189**(4): p. 184-206.
35. García, A., González, M., Llano-Ponte, R., and Labidi, J., *Energy optimization of a kraft pulp mill.* Computer Aided Chemical Engineering, 2009. **27**: p. 417-422.

36. Koufos, D. and Retsina, T., *Practical energy and water management through pinch analysis for the pulp and paper industry.* Water Science and Technology, 2001. **43**: p. 327-332.

37. Wising, U., Berntsson, T., and Stuart, P., *The potential for energy savings when reducing the water consumption in a Kraft Pulp Mill.* Applied Thermal Engineering, 2005. **25**: p. 1057-1066.

38. Savulescu, L., Poulin, B., Hammache, A., Bédard, S., and Gennaoui, S., *Water and energy savings at a kraft paperboard mill using process integration.* Pulp and Paper Canada, 2005. **106**(9): p. 29-31.

39. Savulescu, L.E. and Alva-Argaez, A., *Direct heat transfer considerations for improving energy efficiency in pulp and paper Kraft mills.* Energy, 2008. **33**(10): p. 1562-1571.

40. Alva-Argáez, A., Savulescu, L., and Poulin, B., *A process integration-based decision support system for the identification of water and energy efficiency improvements in the pulp and paper industry.* Pulp and Paper Canada, 2009. **109-110**(12-1): p. 43-46.

41. Polley, G.T., Picón-Núñez, M., and López-Maciel, J.D.J., *Design of water and heat recovery networks for the simultaneous minimisation of water and energy consumption.* Applied Thermal Engineering, 2010. **30**(16): p. 2290-2299.

42. Mateos-Espejel, E., Savulescu, L., Maréchal, F., and Paris, J., *Systems interactions analysis for the energy efficiency improvement of a Kraft process.* Energy, 2010. **35**(12): p. 5132-5142.

43. Mateos-Espejel, E., Savulescu, L., Maréchal, F., and Paris, J., *Unified methodology for thermal energy efficiency improvement: Application to Kraft process.* Chemical Engineering Science, 2011. **66**(2): p. 135-151.

44. Lovelady, E.M., *Integrated Approaches to the Optimal Design of Multiscale Systems*, in *Office of Graduate Studies*. 2008, Texas A&M University.

45. Klugman, S., Karlsson, M., and Moshfegh, B., *A Swedish integrated pulp and paper mill-Energy optimisation and local heat cooperation.* Energy Policy, 2009. **37**(7): p. 2514-2524.

46. Ji, X., Lundgren, J., Wang, C., Dahl, J., and Grip, C.E. *Process simulation and energy optimization for the pulp and paper mill*. 2010. Chemical Engineering Transactions.

47. Marshman, D.J., Chmelyk, T., Sidhu, M.S., Gopaluni, R.B., and Dumont, G.A., *Energy optimization in a pulp and paper mill cogeneration facility.* Applied Energy, 2010. **87**(11): p. 3514-3525.

48. Chew, I.M.L., Foo, D.C.Y., Bonhivers, J.C., Stuart, P., Alva-Argaez, A., and Savulescu, L.E., *A model-based approach for simultaneous water and energy reduction in a pulp and paper mill.* Applied Thermal Engineering, 2013. **51**(1-2): p. 393-400.
49. Ragauskas, A.J., Williams, C.K., Davison, B.H., Britovsek, G., Cairney, J., Eckert, C.A., Frederick Jr, W.J., Hallett, J.P., Leak, D.J., Liotta, C.L., Mielenz, J.R., Murphy, R., Templer, R., and Tschaplinski, T., *The path forward for biofuels and biomaterials.* Science, 2006. **311**(5760): p. 484-489.
50. Fatih Demirbas, M., *Biorefineries for biofuel upgrading: A critical review.* Applied Energy, 2009. **86**(SUPPL. 1): p. S151-S161.
51. Naik, S.N., Goud, V.V., Rout, P.K., and Dalai, A.K., *Production of first and second generation biofuels: A comprehensive review.* Renewable and Sustainable Energy Reviews, 2010. **14**(2): p. 578-597.
52. Kadam, K.L., Chin, C.Y., and Brown, L.W., *Flexible biorefinery for producing fermentation sugars, lignin and pulp from corn stover.* Journal of Industrial Microbiology and Biotechnology, 2008. **35**(5): p. 331-341.
53. Ponce-Ortega, J.M., Pham, V., El-Halwagi, M.M., and El-Baz, A.A., *A disjunctive programming formulation for the optimal design of biorefinery configurations.* Industrial and Engineering Chemistry Research, 2012. **51**(8): p. 3381-3400.
54. Fernando, S., Adhikari, S., Chandrapal, C., and Murali, N., *Biorefineries: Current status, challenges, and future direction.* Energy and Fuels, 2006. **20**(4): p. 1727-1737.
55. Kamm, B. and Kamm, M., *Principles of biorefineries.* Applied Microbiology and Biotechnology, 2004. **64**(2): p. 137-145.
56. Cherubini, F., *The biorefinery concept: Using biomass instead of oil for producing energy and chemicals.* Energy Conversion and Management, 2010. **51**(7): p. 1412-1421.
57. Ng, D.K.S., *Automated targeting for the synthesis of an integrated biorefinery.* Chemical Engineering Journal, 2010. **162**(1): p. 67-74.
58. Ng, D.K.S. *Automated targeting for the synthesis of an integrated biorefinery with multiple products*. 2010. Chemical Engineering Transactions.
59. Tay, D.H.S., Ng, D.K.S., Kheireddine, H., and El-Halwagi, M.M., *Synthesis of an integrated biorefinery via the C-H-O ternary diagram.* Clean Technologies and Environmental Policy, 2011. **13**(4): p. 567-579.

60. Azapagic, A., *Sustainability considerations for integrated biorefineries.* Trends in Biotechnology, 2014. **32**(1): p. 1-4.
61. Pettersson, K., Wetterlund, E., Athanassiadis, D., Lundmark, R., Ehn, C., Lundgren, J., and Berglin, N., *Integration of next-generation biofuel production in the Swedish forest industry - A geographically explicit approach.* Applied Energy, 2015. **154**: p. 317-332.
62. Aparisi, D., *Social aspects of industrial symbiosis networks*. 2010, UCL (University College London).
63. Gibbs, D., Deutz, P., and Proctor, A., *Industrial ecology and eco-industrial development: A potential paradigm for local and regional development?* Regional Studies, 2005. **39**(2): p. 171-183.
64. Bellman, R.E. and Zadeh, L.A., *DECISION-MAKING IN A FUZZY ENVIRONMENT.* Management Science, 1970. **17**(4): p. b-141-64.
65. Zimmermann, H.J., *Fuzzy programming and linear programming with several objective functions.* Fuzzy Sets and Systems, 1978. **1**(1): p. 45-55.
66. Tan, R.R., Aviso, K.B., Barilea, I.U., Culaba, A.B., and Cruz, J.B., *A fuzzy multi-regional input-output optimization model for biomass production and trade under resource and footprint constraints.* Applied Energy, 2012. **90**(1): p. 154-160.
67. Kasivisvanathan, H., Barilea, I.D.U., Ng, D.K.S., and Tan, R.R., *Optimal operational adjustment in multi-functional energy systems in response to process inoperability.* Applied Energy, 2013. **102**: p. 492-500.
68. Myerson, R.B., *Game Theory: Analysis of Conflict*. 1997: Harvard University Press.
69. Boix, M., Montastruc, L., Azzaro-Pantel, C., and Domenech, S., *Optimization methods applied to the design of eco-industrial parks: A literature review.* Journal of Cleaner Production, 2015. **87**(1): p. 303-317.
70. McCain, R., *Game Theory: A Non-Technical Introduction to the Analysis of Strategy*. 2003: South-Western College.
71. Maschler, M., Solan, E., and Zamir, S., *Game Theory: An Introduction*. 2013: Cambridge University Press.
72. Chew, I.M.L., Tan, R.R., Foo, D.C.Y., and Chiu, A.S.F., *Game theory approach to the analysis of inter-plant water integration in an eco-industrial park.* Journal of Cleaner Production, 2009. **17**(18): p. 1611-1619.
73. Chew, I.M.L., Thillaivarrna, S.L., Tan, R.R., and Foo, D.C.Y., *Analysis of inter-plant water integration with indirect integration schemes through game theory approach:*

Pareto optimal solution with interventions. Clean Technologies and Environmental Policy, 2011. **13**(1): p. 49-62.

74. Hiete, M., Ludwig, J., and Schultmann, F., *Intercompany Energy Integration: Adaptation of Thermal Pinch Analysis and Allocation of Savings.* Journal of Industrial Ecology, 2012. **16**(5): p. 689-698.
75. Singh, A. and Lou, H.H., *Hierarchical pareto optimization for the sustainable development of industrial ecosystems.* Industrial and Engineering Chemistry Research, 2006. **45**(9): p. 3265-3279.
76. Maali, Y., *A multiobjective approach for solving cooperative n-person games.* International Journal of Electrical Power and Energy Systems, 2009. **31**(10): p. 608-610.
77. *Freshwater use by sector at the beginning of the 2000s*. [cited 2013 September 20]; Available from: http://www.unep.org/dewa/vitalwater/article48.html.
78. Liu, S., Lu, H., Hu, R., Shupe, A., Lin, L., and Liang, B., *A sustainable woody biomass biorefinery.* Biotechnology Advances, 2012. **30**(4): p. 785-810.
79. *Pulp and Paper Capacities (2010-2015)*, in *Food & Agricultural Organization*. 2011.
80. Linnhoff, B., Mason, D.R., and Wardle, I., *Understanding heat exchanger networks.* Computers and Chemical Engineering, 1979. **3**(1-4): p. 295-302.
81. Linnhoff, B. and Hindmarsh, E., *The pinch design method for heat exchanger networks.* Chemical Engineering Science, 1983. **38**(5): p. 745-763.
82. Phillips, R.B., Jameel, H., and Chang, H.M., *Integration of pulp and paper technology with bioethanol production.* Biotechnology for Biofuels, 2013. **6**(1).
83. Talebnia, F., Karakashev, D., and Angelidaki, I., *Production of bioethanol from wheat straw: An overview on pretreatment, hydrolysis and fermentation.* Bioresource Technology, 2010. **101**(13): p. 4744-4753.
84. Sjöde, A., Alriksson, B., Jönsson, L.J., and Nilvebrant, N.O., *The potential in bioethanol production from waste fiber sludges in pulp mill-based biorefineries.* Applied Biochemistry and Biotechnology, 2007. **137-140**(1-12): p. 327-337.
85. Prasetyo, J. and Park, E.Y., *Waste paper sludge as a potential biomass for bio-ethanol production.* Korean Journal of Chemical Engineering, 2013. **30**(2): p. 253-261.
86. Stoica, A., Sandberg, M., and Holby, O., *Energy use and recovery strategies within wastewater treatment and sludge handling at pulp and paper mills.* Bioresource Technology, 2009. **100**(14): p. 3497-3505.

87. Rikard Gebart, B., Wiinikka, H., Marklund, M., Carlsson, P., Grönberg, C., Weiland, F., Johansson, A.C., and Öhrman, O., *Recent advances in the understanding of pressurized black liquor gasification.* Cellulose Chemistry and Technology, 2011. **45**(7-8): p. 521-526.
88. Van Heiningen, A., *Converting a kraft pulp mill into an integrated forest biorefinery.* Pulp and Paper Canada, 2006. **107**(6): p. 38-43.
89. Naqvi, M., Yan, J., and Dahlquist, E., *Black liquor gasification integrated in pulp and paper mills: A critical review.* Bioresource Technology, 2010. **101**(21): p. 8001-8015.
90. Bajpai, P., *Biorefinery in the Pulp and Paper Industry*. 2013.
91. Larson, E.D., Consonni, S., Katofsky, R.E., Iisa, K., and James Frederick Jr, W., *An assessment of gasification-based biorefining at kraft pulp and paper mills in the United States, Part A: Background and assumptions.* Tappi Journal, 2008. **7**(11): p. 8-14.
92. Sammons Jr, N., Eden, M., Yuan, W., Cullinan, H., and Aksoy, B., *A flexible framework for optimal biorefinery product allocation.* Environmental Progress, 2007. **26**(4): p. 349-354.
93. Fornell, R., Berntsson, T., and Åsblad, A., *Techno-economic analysis of a kraft pulp-mill-based biorefinery producing both ethanol and dimethyl ether.* Energy, 2013. **50**(1): p. 83-92.
94. Dansereau, L.P., El-Halwagi, M., Mansoornejad, B., and Stuart, P., *Framework for margins-based planning: Forest biorefinery case study.* Computers & Chemical Engineering, 2014. **63**(0): p. 34-50.
95. Pettersson, K. and Harvey, S., *Comparison of black liquor gasification with other pulping biorefinery concepts – Systems analysis of economic performance and CO2 emissions.* Energy, 2012. **37**(1): p. 136-153.
96. Pettersson, K. and Harvey, S., *CO2 emission balances for different black liquor gasification biorefinery concepts for production of electricity or second-generation liquid biofuels.* Energy, 2010. **35**(2): p. 1101-1106.
97. Joelsson, J.M. and Gustavsson, L., *Reductions in greenhouse gas emissions and oil use by DME (di-methyl ether) and FT (Fischer-Tropsch) diesel production in chemical pulp mills.* Energy, 2012. **39**(1): p. 363-374.
98. Naqvi, M., Yan, J., and Dahlquist, E., *Synthetic gas production from dry black liquor gasification process using direct causticization with CO2 capture.* Applied Energy, 2012. **97**: p. 49-55.

99. Biermann, C.J., *Chapter 4: Kraft Spent Liquor Recovery*, in *Handbook of Pulping and Papermaking*. 1996, Academic Press: San Diego, California, USA.

100. Larson, E.D., Consonni, S., Katofsky, R.E., Lisa, K., and James Frederick Jr, W., *A Cost-Benefit Assessment of Gasification-Based Biorefinery in the Kraft Pulp and Paper Industry*. 2006, Princeton University: Princeton, NJ,USA.

101. Sammons Jr, N.E., *A Framework for Optimal Biomass-Based Polygeneration Facility Product Allocation*. 2009, Auburn University: Auburn, Alabama, USA.

102. Gau, C.-Y. and Schrage, L., *Implementation and Testing of a Branch-and-Bound Based Method for Deterministic Global Optimization: Operations Research Applications*, in *Frontiers in Global Optimization*, C.A. Floudas and P. Pardalos, Editors. 2004, Springer US. p. 145-164.

103. *LINGO - The Modeling Language and Optimizer*. 2015, LINDO SYSTEMS INC.: Chicago, Illinois, USA.

104. Sinnott, R. and Towler, G.P., *Chemical Engineering Design*. 5th ed. 2009, Oxford, UK: Elsevier Butterworth-Heinemann.

105. Hardy, C. and Graedel, T.E., *Industrial ecosystems as food webs.* Journal of Industrial Ecology, 2002. **6**(1): p. 29-38.

106. Wright, R.A., Côté, R.P., Duffy, J., and Brazner, J., *Diversity and connectance in an industrial context: The case of burnside industrial park.* Journal of Industrial Ecology, 2009. **13**(4): p. 551-564.

107. Tiejun, D., *Two quantitative indices for the planning and evaluation of eco-industrial parks.* Resources, Conservation and Recycling, 2010. **54**(7): p. 442-448.

108. Chew, I.M.L., Foo, D.C.Y., Lam, H.L., Bonhivers, J.C., Stuart, P., Savulescu, L.E., and Alva-Argaez, A., *Simultaneous water and energy optimization for a pulp and paper mill.* Chemical Engineering Transactions, 2011. **25**: p. 441-446.

109. Lee, S.H., Ng, R.T.L., Ng, D.K.S., Foo, D.C.Y., and Chew, I.M.L., *Synthesis of resource conservation networks in an integrated pulp and paper biorefinery.* Industrial and Engineering Chemistry Research, 2014. **53**(25): p. 10417-10428.

110. Frosch, R.A. and Gallopoulos, N.E., *Strategies for Manufacturing*, in *Scientific American*. 1989, Nature Publishing Group: United States.

111. Moshkelani, M., Marinova, M., Perrier, M., and Paris, J., *The forest biorefinery and its implementation in the pulp and paper industry: Energy overview.* Applied Thermal Engineering, 2013. **50**(2): p. 1427-1436.

112. Kosugi, T., Tokimatsu, K., Kurosawa, A., Itsubo, N., Yagita, H., and Sakagami, M., *Internalization of the external costs of global environmental damage in an integrated assessment model.* Energy Policy, 2009. **37**(7): p. 2664-2678.

113. Rafione, T., Marinova, M., Montastruc, L., and Paris, J., *The Green Integrated Forest Biorefinery: An innovative concept for the pulp and paper mills.* Applied Thermal Engineering, 2014. **73**(1): p. 72-79.

114. Tudor, T., Adam, E., and Bates, M., *Drivers and limitations for the successful development and functioning of EIPs (eco-industrial parks): A literature review.* Ecological Economics, 2007. **61**(2-3): p. 199-207.

115. Zhu, L., Zhou, J., Cui, Z., and Liu, L., *A method for controlling enterprises access to an eco-industrial park.* Science of the Total Environment, 2010. **408**(20): p. 4817-4825.

116. Wang, G., Feng, X., and Chu, K.H., *A novel approach for stability analysis of industrial symbiosis systems.* Journal of Cleaner Production, 2013. **39**: p. 9-16.

117. Benjamin, M.F.D., Tan, R.R., and Razon, L.F., *A methodology for criticality analysis in integrated energy systems.* Clean Technologies and Environmental Policy, 2014.

118. Tan, R.R., Aviso, K.B., Cruz Jr, J.B., and Culaba, A.B., *A note on an extended fuzzy bi-level optimization approach for water exchange in eco-industrial parks with hub topology.* Process Safety and Environmental Protection, 2011. **89**(2): p. 106-111.

119. Winter, E., *Chapter 53 The shapley value*, in *Handbook of Game Theory with Economic Applications*, A. Robert and H. Sergiu, Editors. 2002, Elsevier. p. 2025-2054.

120. Hamaguchi, M., Cardoso, M., and Vakkilainen, E., *Alternative technologies for biofuels production in kraft pulp mills-potential and prospects.* Energies, 2012. **5**(7): p. 2288-2309.

121. Mao, H., Genco, J.M., Yoon, S.H., van Heiningen, A., and Pendse, H., *Technical economic evaluation of a hardwood biorefinery using the "near-neutral" hemicellulose pre-extraction process.* Journal of Biobased Materials and Bioenergy, 2008. **2**(2): p. 177-185.

122. Eriksson, H. and Harvey, S., *Black liquor gasification-consequences for both industry and society.* Energy, 2004. **29**(4): p. 581-612.

123. Harvey, S. and Facchini, B., *Predicting black liquor gasification combined cycle powerhouse performance accounting for off-design gas turbine operation.* Applied Thermal Engineering, 2004. **24**(1): p. 111-126.

124. Andersson, E. and Harvey, S., *System analysis of hydrogen production from gasified black liquor.* Energy, 2006. **31**(15): p. 3426-3434.

125. Wetterlund, E., Karlsson, M., and Harvey, S., *Biomass gasification integrated with a pulp and paper mill - The need for economic policies promoting biofuels*, in *Chemical Engineering Transactions*. 2010. p. 1207-1212.

126. Tan, R.R., Andiappan, V., Wan, Y.K., Ng, R.T.L., and Ng, D.K.S., *An optimization-based cooperative game approach for systematic allocation of costs and benefits in interplant process integration.* Chemical Engineering Research and Design, 2016. **106**: p. 43-58.

127. Goh, W.S., Wan, Y.K., Tay, C.K., Ng, R.T.L., and Ng, D.K.S., *Automated targeting model for synthesis of heat exchanger network with utility systems.* Applied Energy, 2015.

128. Brennan, D.J., *Process Industry Economics (Chapter 5)*. 1998: The Institution of Chemical Engineers.

129. Montastruc, L., Ajao, O., Marinova, M., Do Carmo, C.B., and Domenech, S., *Hemicellulose biorefinery for furfural production: Energy requirement analysis and minimization.* J-FOR, 2011. **1**(3): p. 48-53.

Appendices

Appendix 1: Supporting Information for Chapter 3

Table A1.1 shows the water flow rates and DR for each of the washers in BSWS. **Table A1.2** presents the conversion factors from biomass into intermediates and final products for each biorefinery pathway. **Table A1.3** summarizes the processing cost (including fixed and variable cost) of each alternative biorefinery pathways (expressed per primary product output). **Table A1.4** presents the price of biorefinery product, energy and freshwater. Note that biofuel and electricity prices are collected from year 2005.

Table A1.1. Washers flow rate and displacement ratio (DR) in BSWS [48]

Process equipment	DR	Water flow rates (kg/ton of pulp)			
		Pulp inlet	Shower	Filtrate	Pulp outlet
EMCC	0.65	9,457	4,998	10,505	3,950
Diffuser 1	0.90	7,612	12,494	12,852	7,254
Diffuser 2	0.90	7,254	12,494	12,494	7,254
Decker Washer	0.75	57,439	9,500	59,803	7,136
Twin roll press	-	26,829	-	23,807	3,022
Washer 1	0.70	61,981	4,500	60,681	5,800
Washer 2	0.72	71,662	6,000	70,869	6,793
Washer 3	0.70	71,662	6,000	71,614	6,048

Table A1.2. Conversion factors for each biorefinery pathway

Pathway	Conversion factor	Intermediates/ products	Value
0101	Y_{0101}^{MPST}	Medium Pressure Steam	0.8928 (kg MPS/ton of pulp)/(kg BL/ton of pulp)
	Y_{0101}^{LPST}	Low Pressure Steam	1.717 (kg LPS/ton of pulp)/(kg BL/ton of pulp)
	Y_{0101}^{ELEC}	Electricity	4.537×10^{-4} (MWh electricity)/(kg BL/ton of pulp)
0102	Y_{0101}^{SYN}	Syngas	1.688 (kg syngas/ton of pulp)/(kg BL/ton of pulp)

Pathway	Conversion factor	Products	Value
0201	Y_{0201}^{MPST}	Medium Pressure Steam	0.5474 (kg MPS/ton of pulp)/(kg BL/ton of pulp)
	Y_{0201}^{LPST}	Low Pressure Steam	1.067 (kg LPS/ton of pulp)/(kg BL/ton of pulp)
	Y_{0201}^{ELEC}	Electricity	5.274×10^{-4} (MWh electricity)/(kg BL/ton of pulp)
0202	Y_{0202}^{DME}	DME	1.455×10^{-4}

			(m^3 DME/ton of pulp)/(kg syngas/ton of pulp)
	Y_{0202}^{MPST}	Medium Pressure Steam	0.5474 (kg MPS/ton of pulp)/(kg BL/ton of pulp)
	Y_{0202}^{LPST}	Low Pressure Steam	1.067 (kg LPS/ton of pulp)/(kg BL/ton of pulp)
	Y_{0202}^{ELEC}	Electricity	2.589×10^{-6} (MWh electricity)/(kg BL/ton of pulp)
0203	Y_{0203}^{DME}	DME	1.455×10^{-4} (m^3 DME/ton of pulp)/(kg syngas/ton of pulp)
	Y_{0203}^{MPST}	Medium Pressure Steam	0.5474 (kg MPS/ton of pulp)/(kg BL/ton of pulp)
	Y_{0203}^{LPST}	Low Pressure Steam	1.067 (kg LPS/ton of pulp)/(kg BL/ton of pulp)
	Y_{0203}^{ELEC}	Electricity	4.061×10^{-4} (MWh electricity)/(kg BL/ton of pulp)
0204	Y_{0204}^{DME}	DME	6.428×10^{-5} (m^3 DME/ton of pulp)/(kg syngas/ton of pulp)
	Y_{0204}^{MPST}	Medium Pressure Steam	0.5474 (kg MPS/ton of pulp)/(kg BL/ton of pulp)
	Y_{0204}^{LPST}	Low Pressure Steam	1.067 (kg LPS/ton of pulp)/(kg BL/ton of pulp)
	Y_{0204}^{ELEC}	Electricity	4.185×10^{-4} (MWh electricity)/(kg BL/ton of pulp)
0205	Y_{0205}^{FT}	FT fuel	5.943×10^{-5} (m^3 FT/ton of pulp)/(kg syngas/ton of pulp)
	Y_{0205}^{MPST}	Medium Pressure Steam	0.5474 (kg MPS/ton of pulp)/(kg BL/ton of pulp)
	Y_{0205}^{LPST}	Low Pressure Steam	1.067 (kg LPS/ton of pulp)/(kg BL/ton of pulp)
	Y_{0205}^{ELEC}	Electricity	4.053×10^{-4} (MWh electricity)/(kg BL/ton of pulp)
0206	Y_{0206}^{FT}	FT fuel	5.943×10^{-5} (m^3 FT/ton of pulp)/(kg syngas/ton of pulp)

	Y_{0206}^{MPST}	Medium Pressure Steam	0.5474 (kg MPS/ton of pulp)/(kg BL/ton of pulp)
	Y_{0206}^{LPST}	Low Pressure Steam	1.067 (kg LPS/ton of pulp)/(kg BL/ton of pulp)
	Y_{0206}^{ELEC}	Electricity	1.058×10^{-4} (MWh electricity)/(kg BL/ton of pulp)
0207	Y_{0207}^{FT}	FT fuel	1.826×10^{-5} (m^3 FT/ton of pulp)/(kg syngas/ton of pulp)
	Y_{0207}^{MPST}	Medium Pressure Steam	0.5474 (kg MPS/ton of pulp)/(kg BL/ton of pulp)
	Y_{0207}^{LPST}	Low Pressure Steam	1.067 (kg LPS/ton of pulp)/(kg BL/ton of pulp)
	Y_{0207}^{ELEC}	Electricity	3.573×10^{-4} (MWh electricity)/(kg BL/ton of pulp)
0208	Y_{0208}^{MA}	MA fuel	3.520×10^{-5} (m^3 MA/ton of pulp)/(kg syngas/ton of pulp)
	Y_{0208}^{MPST}	Medium Pressure Steam	0.5474 (kg MPS/ton of pulp)/(kg BL/ton of pulp)
	Y_{0208}^{LPST}	Low Pressure Steam	1.067 (kg LPS/ton of pulp)/(kg BL/ton of pulp)
	Y_{0208}^{ELEC}	Electricity	4.247×10^{-4} (MWh electricity)/(kg BL/ton of pulp)

Table A1.3. Processing cost of each biorefinery pathway

Pathway, *k*	**Primary output, *l***	**Fixed and variable cost per primary output, P_{kl}**
0101	Steam	1.007×10^{-2} /kg steam
0102	Syngas	5.189×10^{-3} /kg syngas
Pathway, *k'*	**Primary output, *l'***	**Fixed and variable cost per primary output, $P_{k'l'}$**
0201	Electricity	39.65 /MWh
0202	DME	172 /m^3 DME
0203	DME	288 /m^3 DME
0204	DME	479 /m^3 DME
0205	FT fuel	541 /m^3 FT fuel
0206	FT fuel	910 /m^3 FT fuel
0207	FT fuel	294 /m^3 FT fuel
0208	MA fuel	1,059 /m^3 MA fuel

Table A1.4. Price of biorefinery product, energy and freshwater

Item	Cost (USD)
Final Product	
DME	261 /m^3
FT fuel	407 /m^3
MA fuel	468 /m^3
Energy	
Exported electricity to the grid	40 /MWh
Purchased electricity for BSWS	45 /MWh
Process steam	0.0039 /kg
Freshwater	1 /m^3

Appendix 2: LINGO Model Formulation for Chapter 3

```
!=========================================================================;
!OBJECTIVE FUNCTION;
!=========================================================================;
MODEL:
MAX = GROSS_PROFIT;
@FREE(GROSS_PROFIT);

!Base Case;
BC_Energy = 6.74e6;          !kJ/ton_pulp;
BC_Steam = 6.74e6/2786;      !kg/ton_pulp;

GROSS_PROFIT = REVENUES - COSTS;                             !$/yr;

!REVENUES;
!1MWh = 3.6e6 kJ;
!1kJ  = 2.778e-7 MWh;
REVENUES = Annual_Product + Annual_Elec + Annual_Steam;      !$/yr;

Annual_Product = ((ProdDMEa + ProdDMEb + ProdDMEc)*P_DME + (ProdFTa +
ProdFTb + ProdFTc)*P_FT + ProdMA*P_MA)*PR*330;  !$/yr;
      P_DME = 0.99; !$/gal;
      P_FT  = 1.54; !$/gal;
      P_MA  = 1.77; !$/gal;

Annual_Elec = Total_elec_MWh*Price_elec_MWh*PR*330;          !$/yr;
      !Price_elec_KJ = 4.8/1e6;                              !$/kJ;
      !Price_elec_MWh = 4.8/1e6*3.6e6;!                      !$/MWh;
      Price_elec_MWh = 40;                                   !$/MWh;

Annual_Steam = Total_st_sold*Price_steam*PR*330;             !$/yr;
      !Price_steam      = 1.534;                             !$/k_lb_steam;
      Price_steam = 3.382e-3;                                !$/kg_steam;

!Total_st_sold     = MPS_sold + Total_LPS;       !kg_steam/ton_pulp;
!Total_MPS         = MPS_sold + MPS_BSWS;        !kg/ton_pulp;

Total_st_req = LPS_BSWS + LPS_bought;            !kg/ton_pulp;
Total_st_req = m_MEE_MPS + m_O2_MPS;             !kg/ton_pulp;
LPS_energy_BSWS = LPS_bought*2786;               !kJ/ton_pulp;
!MPS_energy_MWh   = MPS_energy_BSWS/3.6e6;       !kJ/ton_pulp;

!COSTS;
COSTS = Annual_FW + Annual_Energy + Annual_Processing;             !$/yr;

Annual_FW = Total_FW*Cost_FW*PR*330;                               !$/yr;
      Total_FW     = FW_Shower + FW_Dilution + FW_TRP; !kg_H2O/ton_pulp;
      Cost_FW      = 0.001;                           !$/kg_H2O;

Annual_Energy = LPS_energy_BSWS*Cost_Energy*PR*330;                !$/yr;
      !Total_Energy = E_MEE + E_O2_react;
      !kJ/ton_pulp;
      Cost_Energy   = 12.5/1e6;                                    !$/kJ;
      !Cost_Energy   = 5/1e6;                                      !$/kJ;
      !Cost_Energy   = 18;                                         !$/MWh;

Annual_Processing = Processing1 + Processing2;               !$/yr;
      !Processing of 1st stage pathway;
      Processing1 = (ProdTOM_st*PATHcost01 + ProdSYN*PATHcost02)*PR*330;
      !$/yr;
```

```
    !PATHcost01 = 4.568;                  !$/k_lb_steam;
    PATHcost01 = 4.568*2.20446e-3;        !$/kg_steam;
    PATHcost02 = 5.189e-3;                !$/kg_syn;

    !Processing of 2nd stage pathway;
    Processing2 = (ProdBLGCC_elec*PATHcost0201 + ProdDMEa*PATHcost0202 +
    ProdDMEb*PATHcost0203 + ProdDMEc*PATHcost0204 + ProdFTa*PATHcost0205
    + ProdFTb*PATHcost0206 + ProdFTc*PATHcost0207 +
    ProdMA*PATHcost0208)*PR*330;

    PATHcost0201 = 39.65;    !$/MWh;
    PATHcost0202 = 0.6508;   !$/gal_DME;
    PATHcost0203 = 1.090;    !$/gal_DME;
    PATHcost0204 = 1.813;    !$/gal_DME;
    PATHcost0205 = 2.047;    !$/gal_FT;
    PATHcost0206 = 3.445;    !$/gal_FT;
    PATHcost0207 = 1.114;    !$/gal_FT;
    PATHcost0208 = 4.008;    !$/gal_MA;


!==========================================================================;
!PULP WASHING SECTION;
!==========================================================================;
!Operation Hour  = 330 d/yr;

!Variables Defined;
PR = 600;                !ton_pulp/day; !PR=260=35.6; !PR=1350=35kg/s;
LB = 1;                  !Flowrate lower bound, kg_H2O/ton_pulp;
C_FW = 0;                !DS conc of FW;
A_FW = 45;               !Temp of FW;

!Washers flowrate from CADSIM [kg_H20/ton_pulp], [1=EMCC, 2=Diff 1, 3=Diff
2, 4=Decker, 5=Washer 1, 6=Washer 2, 7=PreDO];
S1 = 4997.68;
S2 = 12494.02;
S3 = 12494.02;
S4 = 9500;
S5 = 4500;
S6 = 6000;
S7 = 6000;    !Shower (into washer);

P0 = 9456.73;
D2 = 7612.08;
D3 = 7253.70;
D4 = 57438.49;
D5 = 61981;
D6 = 71662;
D7 = 71662; !Pulp inlet after dilution point;

F1 = 10504.65;
F2 = 12852.41;
F3 = 12494.02;
F4 = 59802.65;
F5 = 60681;
F6 = 70869;
F7 = 71614; !Filtrate (out from washer);

P1 = 3949.76;
P2 = 7253.69;
P3 = 7253.70;
P4 = 7135.84;
```

```
P5 = 5800;
P6 = 6793;
P7 = 6048;   !Pulp discharge;

      !Twin Roll Press (TRP) flowrate (no shower);
      TRP_In  = 26829;        !TRP inlet (after dilution from filtrate,
pulp outlet, etc);
      TRP_Fil = 23807;        !TRP Pressate/Filtrate;
      TRP_Out = 3022;         !TRP outlet to O2 reactor inlet//pulp
discharge;
      !Displacement ratio (DR) of washers;
[RDR1]      DR1 = 0.65; DR2 = 0.9; DR3 = 0.9; DR4 = 0.75; DR5 = 0.7; DR6 =
0.72; DR7 = 0.7;

!DR constraints;
[RDR] CD1 - CP1 = DR1*(CD1 - CS1);
CD2 - CP2 = DR2*(CD2 - CS2);
CD3 - CP3 = DR3*(CD3 - CS3);
CD4 - CP4 = DR4*(CD4 - CS4);
CD5 - CP5 = DR5*(CD5 - CS5);
CD6 - CP6 = DR6*(CD6 - CS6);
CD7 - CP7 = DR7*(CD7 - CS7);

!==========================================================================;
!MASS BALANCES;
!==========================================================================;
!Total Balance of Washers;
D1 + S1 = P1 + F1; !Dilution + Shower = Pulp Out + Filtrate;
D2 + S2 = P2 + F2;
D3 + S3 = P3 + F3;
D4 + S4 = P4 + F4;
D5 + S5 = P5 + F5;
D6 + S6 = P6 + F6;
D7 + S7 = P7 + F7;

!DS Balance of Washers;
D1*CD1 + S1*CS1 = P1*CP1 + F1*CF1;
D2*CD2 + S2*CS2 = P2*CP2 + F2*CF2;
D3*CD3 + S3*CS3 = P3*CP3 + F3*CF3;
D4*CD4 + S4*CS4 = P4*CP4 + F4*CF4;
D5*CD5 + S5*CS5 = P5*CP5 + F5*CF5;
D6*CD6 + S6*CS6 = P6*CP6 + F6*CF6;
D7*CD7 + S7*CS7 = P7*CP7 + F7*CF7;

!TRP Balance;
TRP_In = TRP_Fil + TRP_Out;
TRP_In*CTRP_In = (TRP_Fil + TRP_Out)*CTRP_out;
      !INLET (Dilution TRP Balance) (Total and DS);
      TRP_In = FW_TRP + (TRPF1 + TRPF2 + TRPF3 + TRPF4 + TRPF5 + TRPF6 +
TRPF7) + TRP_self_recy + P4; !P4 = pulp outlet from washer #4;
      TRP_In*CTRP_In = FW_TRP*C_FW+ (TRPF1*CF1 + TRPF2*CF2 + TRPF3*CF3 +
TRPF4*CF4 + TRPF5*CF5 + TRPF6*CF6 + TRPF7*CF7) + TRP_self_recy*CTRP_out+
P4*CP4;
      !Filtrate Balance (Total and DS);
      TRP_Fil = (TRPS1 + TRPS2 + TRPS3 + TRPS4 + TRPS5 + TRPS6 + TRPS7) +
(TRPD1 + TRPD2 + TRPD3 + TRPD4 + TRPD5 + TRPD6 + TRPD7) + TRP_self_recy;
      !TRP_Fil*C_Fil= ((TRPS1 + TRPS2 + TRPS3 + TRPS4 + TRPS5 + TRPS6 +
TRPS7) + (TRPD1 + TRPD2 + TRPD3 + TRPD4 + TRPD5 + TRPD6 + TRPD7) +
TRP_self_recy)*C_Fil;
      CTRP_in = CTRP_out;                         !no changes in DS
concentration [TRP assumption];
```

```
!O2 Delignification Reactor Balance;
TRP_Out*CTRP_out = 19.44*1000;                  !DS mass upper limit before
entering the reactor;
OR_out = TRP_Out;                               !Equal flowrate at reactor
inlet and outlet;
OR_out*CR_out = TRP_Out*CTRP_out + 29*1000;     !DS mass is increased by
29kg/kgpulp after the delignification process;

!============================================================================;
!SINK BALANCES;
!============================================================================;
!Shower Balance;
S1 = FWS1 + FTS11 + FTS21 + FTS31 + FTS41 + FTS51 + FTS61 + FTS71 + TRPS1;
!FWS = FW to shower j;
S2 = FWS2 + FTS12 + FTS22 + FTS32 + FTS42 + FTS52 + FTS62 + FTS72 + TRPS2;
!FTSij = filtrate i to shower j;
S3 = FWS3 + FTS13 + FTS23 + FTS33 + FTS43 + FTS53 + FTS63 + FTS73 + TRPS3;
S4 = FWS4 + FTS14 + FTS24 + FTS34 + FTS44 + FTS54 + FTS64 + FTS74 + TRPS4;
S5 = FWS5 + FTS15 + FTS25 + FTS35 + FTS45 + FTS55 + FTS65 + FTS75 + TRPS5;
S6 = FWS6 + FTS16 + FTS26 + FTS36 + FTS46 + FTS56 + FTS66 + FTS76 + TRPS6;
S7 = FWS7 + FTS17 + FTS27 + FTS37 + FTS47 + FTS57 + FTS67 + FTS77 + TRPS7;
      !DS Shower Balance;
      S1*CS1 = FWS1*C_FW + FTS11*CF1 + FTS21*CF2 + FTS31*CF3 + FTS41*CF4 +
FTS51*CF5 + FTS61*CF6 + FTS71*CF7 + TRPS1*CTRP_out;
      S2*CS2 = FWS2*C_FW + FTS12*CF1 + FTS22*CF2 + FTS32*CF3 + FTS42*CF4 +
FTS52*CF5 + FTS62*CF6 + FTS72*CF7 + TRPS2*CTRP_out;
      S3*CS3 = FWS3*C_FW + FTS13*CF1 + FTS23*CF2 + FTS33*CF3 + FTS43*CF4 +
FTS53*CF5 + FTS63*CF6 + FTS73*CF7 + TRPS3*CTRP_out;
      S4*CS4 = FWS4*C_FW + FTS14*CF1 + FTS24*CF2 + FTS34*CF3 + FTS44*CF4 +
FTS54*CF5 + FTS64*CF6 + FTS74*CF7 + TRPS4*CTRP_out;
      S5*CS5 = FWS5*C_FW + FTS15*CF1 + FTS25*CF2 + FTS35*CF3 + FTS45*CF4 +
FTS55*CF5 + FTS65*CF6 + FTS75*CF7 + TRPS5*CTRP_out;
      S6*CS6 = FWS6*C_FW + FTS16*CF1 + FTS26*CF2 + FTS36*CF3 + FTS46*CF4 +
FTS56*CF5 + FTS66*CF6 + FTS76*CF7 + TRPS6*CTRP_out;
      S7*CS7 = FWS7*C_FW + FTS17*CF1 + FTS27*CF2 + FTS37*CF3 + FTS47*CF4 +
FTS57*CF5 + FTS67*CF6 + FTS77*CF7 + TRPS7*CTRP_out;

      FW_Shower = FWS1 + FWS2 + FWS3 + FWS4 + FWS5 + FWS6 + FWS7;
      CS7 = 0; !FW enter last washer with zero DS;
                              !

!Dilution Balance;
D1 = FWD1 + FTD11 + FTD21 + FTD31 + FTD41 + FTD51 + FTD61 + FTD71 + TRPD1 +
P0; !FWD = FW to dilution j;
D2 = FWD2 + FTD12 + FTD22 + FTD32 + FTD42 + FTD52 + FTD62 + FTD72 + TRPD2 +
P1; !FTDij = filtrate i to dilution j;
D3 = FWD3 + FTD13 + FTD23 + FTD33 + FTD43 + FTD53 + FTD63 + FTD73 + TRPD3 +
P2; !P = pulp outlet from shower i-1 (before dilution);
D4 = FWD4 + FTD14 + FTD24 + FTD34 + FTD44 + FTD54 + FTD64 + FTD74 + TRPD4 +
P3;
D5 = FWD5 + FTD15 + FTD25 + FTD35 + FTD45 + FTD55 + FTD65 + FTD75 + TRPD5 +
OR_out;
D6 = FWD6 + FTD16 + FTD26 + FTD36 + FTD46 + FTD56 + FTD66 + FTD76 + TRPD6 +
P5;
D7 = FWD7 + FTD17 + FTD27 + FTD37 + FTD47 + FTD57 + FTD67 + FTD77 + TRPD7 +
P6;
      !DS Dilution Balance;
      D1*CD1 = FWD1*C_FW + FTD11*CF1 + FTD21*CF2 + FTD31*CF3 + FTD41*CF4 +
FTD51*CF5 + FTD61*CF6 + FTD71*CF7 + TRPD1*CTRP_out + P0*CP0;
```

```
      D2*CD2 = FWD2*C_FW + FTD12*CF1 + FTD22*CF2 + FTD32*CF3 + FTD42*CF4 +
FTD52*CF5 + FTD62*CF6 + FTD72*CF7 + TRPD2*CTRP_out + P1*CP1;
      D3*CD3 = FWD3*C_FW + FTD13*CF1 + FTD23*CF2 + FTD33*CF3 + FTD43*CF4 +
FTD53*CF5 + FTD63*CF6 + FTD73*CF7 + TRPD3*CTRP_out + P2*CP2;
      D4*CD4 = FWD4*C_FW + FTD14*CF1 + FTD24*CF2 + FTD34*CF3 + FTD44*CF4 +
FTD54*CF5 + FTD64*CF6 + FTD74*CF7 + TRPD4*CTRP_out + P3*CP3;
      D5*CD5 = FWD5*C_FW + FTD15*CF1 + FTD25*CF2 + FTD35*CF3 + FTD45*CF4 +
FTD55*CF5 + FTD65*CF6 + FTD75*CF7 + TRPD5*CTRP_out + OR_out*CR_out;
      D6*CD6 = FWD6*C_FW + FTD16*CF1 + FTD26*CF2 + FTD36*CF3 + FTD46*CF4 +
FTD56*CF5 + FTD66*CF6 + FTD76*CF7 + TRPD6*CTRP_out + P5*CP5;
      D7*CD7 = FWD7*C_FW + FTD17*CF1 + FTD27*CF2 + FTD37*CF3 + FTD47*CF4 +
FTD57*CF5 + FTD67*CF6 + FTD77*CF7 + TRPD7*CTRP_out + P6*CP6;

      FW_Dilution = FWD1 + FWD2 + FWD3 + FWD4 + FWD5 + FWD6 + FWD7;
      !CP0 = CD1; !P0 = D1;   !assume no FW or filtrate transfer from any
other streams into EMCC;
      !D1 = FWD1 + FTD11 + FTD21 + FTD31 + FTD41 + FTD51 + FTD61 + FTD71 +
TRPD1 + P0 + Total_BL_recy; !FWD   = FW to dilution j;
      !D1*CD1 >= FWD1*C_FW + FTD11*CF1 + FTD21*CF2 + FTD31*CF3 + FTD41*CF4
+ FTD51*CF5 + FTD61*CF6 + FTD71*CF7 + TRPD1*CTRP_out + P0*CP0 +
Total_BL_recy*CBLRe;

!=========================================================================;
!SOURCE BALANCES;
!=========================================================================;
!Filtrate Balance;
F1 = (FTS11+FTS12+FTS13+FTS14+FTS15+FTS16+FTS17) +
(FTD11+FTD12+FTD13+FTD14+FTD15+FTD16+FTD17)+ TRPF1 + BL1;
F2 = (FTS21+FTS22+FTS23+FTS24+FTS25+FTS26+FTS27) +
(FTD21+FTD22+FTD23+FTD24+FTD25+FTD26+FTD27)+ TRPF2 + BL2;
F3 = (FTS31+FTS32+FTS33+FTS34+FTS35+FTS36+FTS37) +
(FTD31+FTD32+FTD33+FTD34+FTD35+FTD36+FTD37)+ TRPF3 + BL3;
F4 = (FTS41+FTS42+FTS43+FTS44+FTS45+FTS46+FTS47) +
(FTD41+FTD42+FTD43+FTD44+FTD45+FTD46+FTD47)+ TRPF4 + BL4;
F5 = (FTS51+FTS52+FTS53+FTS54+FTS55+FTS56+FTS57) +
(FTD51+FTD52+FTD53+FTD54+FTD55+FTD56+FTD57)+ TRPF5 + BL5;
F6 = (FTS61+FTS62+FTS63+FTS64+FTS65+FTS66+FTS67) +
(FTD61+FTD62+FTD63+FTD64+FTD65+FTD66+FTD67)+ TRPF6 + BL6;
F7 = (FTS71+FTS72+FTS73+FTS74+FTS75+FTS76+FTS77) +
(FTD71+FTD72+FTD73+FTD74+FTD75+FTD76+FTD77)+ TRPF7 + BL7;

      BL1 = WE1 + WR1;
      BL2 = WE2 + WR2;
      BL3 = WE3 + WR3;
      BL4 = WE4 + WR4;
      BL5 = WE5 + WR5;
      BL6 = WE6 + WR6;
      BL7 = WE7 + WR7;
      Total_BL = BL1 + BL2 + BL3 + BL4 + BL5 + BL6 + BL7;
                        !kg_H2O/ton_pulp;

      !BL sent to EMCC washer for recycle;
      BLR = WR1 + WR2 + WR3 + WR4 + WR5 + WR6 + WR7;
      BLR = 2000;

      !BL sent to MEE;
      BLE = WE1 + WE2 + WE3 + WE4 + WE5 + WE6 + WE7;
      BLE*CBLIn = WE1*CF1 + WE2*CF2 + WE3*CF3 + WE4*CF4 + WE5*CF5+ WE6*CF6
+ WE7*CF7;        !kg_H2O/ton_pulp;
      !Total_BL_kgs= (Total_BL1*PR)/(24*60*60);
                        !Change kg_H2O/ton_pulp to kg/s;
```

```
      !CBLIn <= 170;     !Need to specify;
      CP7 = 0.93;        !Final pulp outlet DS conc; !Critical to reach
global after introduction of E section;
      CP0 = 200;         !Fresh pulp DS conc;

!MEE Flow Balance;
BLE = SBL + Vapor;
BLE*CBLIn = SBL*CBLOut + Vapor*CBLVap;
SBL_kgs = (SBL*PR)/(24*60*60);       !Change kg_H2O/ton_pulp to kg/s;
[R22] CBLVap = 0;
      CBLOut >= 800;     !based on Larson's thesis;
      !CBLOut <= 1000;   !based on Larson's thesis;

!==========================================================================;
!ENERGY BALANCES;
!==========================================================================;
!Multiple-Effect Evaporator;
!Energy requirement;
E_MEE = Vapor*2200/4;                           !kJ/ton_pulp, avg spcific
enthalpy of water in MEE is 2200 with MEE efficiency of 4;

!Steam requirement (medium pressure steam);
m_MEE_MPS = E_MEE/H_MEE_MPS;                    !kg/ton_pulp;
H_MEE_MPS = 2786;                               !kJ/kg, enthalpy at 13bar
1300kPa;

!O2 Delignification Reactor;
!Energy requirement;
E_O2_react = TRP_out*4.0*(AR_in - ATRP_out);    !kJ/ton_pulp;
!Steam requirement (medium pressure steam);
m_O2_MPS = E_O2_react/H_O2_MPS;                 !kg/ton_pulp;
H_O2_MPS = 2786;                                !kJ/kg, enthalpy at 13bar
1300kPa;
      AR_in >= 115;

!Energy DS Balance of Washers;
D1*AD1 + S1*AS1 = P1*AP1 + F1*AF1;
D2*AD2 + S2*AS2 = P2*AP2 + F2*AF2;
D3*AD3 + S3*AS3 = P3*AP3 + F3*AF3;
D4*AD4 + S4*AS4 = P4*AP4 + F4*AF4;
D5*AD5 + S5*AS5 = P5*AP5 + F5*AF5;
D6*AD6 + S6*AS6 = P6*AP6 + F6*AF6;
D7*AD7 + S7*AS7 = P7*AP7 + F7*AF7;

!DR constraints (temperature);
AD1 - AP1 = DR1*(AD1 - AS1);
AD2 - AP2 = DR2*(AD2 - AS2);
AD3 - AP3 = DR3*(AD3 - AS3);
AD4 - AP4 = DR4*(AD4 - AS4);
AD5 - AP5 = DR5*(AD5 - AS5);
AD6 - AP6 = DR6*(AD6 - AS6);
AD7 - AP7 = DR7*(AD7 - AS7);

      !Energy (DS) Shower Balance;
      S1*AS1 = FWS1*A_FW + FTS11*AF1 + FTS21*AF2 + FTS31*AF3 + FTS41*AF4 +
FTS51*AF5 + FTS61*AF6 + FTS71*AF7 + TRPS1*ATRP_out;
      S2*AS2 = FWS2*A_FW + FTS12*AF1 + FTS22*AF2 + FTS32*AF3 + FTS42*AF4 +
FTS52*AF5 + FTS62*AF6 + FTS72*AF7 + TRPS2*ATRP_out;
      S3*AS3 = FWS3*A_FW + FTS13*AF1 + FTS23*AF2 + FTS33*AF3 + FTS43*AF4 +
FTS53*AF5 + FTS63*AF6 + FTS73*AF7 + TRPS3*ATRP_out;
```

```
      S4*AS4 = FWS4*A_FW + FTS14*AF1 + FTS24*AF2 + FTS34*AF3 + FTS44*AF4 +
FTS54*AF5 + FTS64*AF6 + FTS74*AF7 + TRPS4*ATRP_out;
      S5*AS5 = FWS5*A_FW + FTS15*AF1 + FTS25*AF2 + FTS35*AF3 + FTS45*AF4 +
FTS55*AF5 + FTS65*AF6 + FTS75*AF7 + TRPS5*ATRP_out;
      S6*AS6 = FWS6*A_FW + FTS16*AF1 + FTS26*AF2 + FTS36*AF3 + FTS46*AF4 +
FTS56*AF5 + FTS66*AF6 + FTS76*AF7 + TRPS6*ATRP_out;
      S7*AS7 = FWS7*A_FW + FTS17*AF1 + FTS27*AF2 + FTS37*AF3 + FTS47*AF4 +
FTS57*AF5 + FTS67*AF6 + FTS77*AF7 + TRPS7*ATRP_out;

      !Energy (DS) Dilution Balance;
      D1*AD1 = FWD1*A_FW + FTD11*AF1 + FTD21*AF2 + FTD31*AF3 + FTD41*AF4 +
FTD51*AF5 + FTD61*AF6 + FTD71*AF7 + TRPD1*ATRP_out + P0*AP0;
      D2*AD2 = FWD2*A_FW + FTD12*AF1 + FTD22*AF2 + FTD32*AF3 + FTD42*AF4 +
FTD52*AF5 + FTD62*AF6 + FTD72*AF7 + TRPD2*ATRP_out + P1*AP1;
      D3*AD3 = FWD3*A_FW + FTD13*AF1 + FTD23*AF2 + FTD33*AF3 + FTD43*AF4 +
FTD53*AF5 + FTD63*AF6 + FTD73*AF7 + TRPD3*ATRP_out + P2*AP2;
      D4*AD4 = FWD4*A_FW + FTD14*AF1 + FTD24*AF2 + FTD34*AF3 + FTD44*AF4 +
FTD54*AF5 + FTD64*AF6 + FTD74*AF7 + TRPD4*ATRP_out + P3*AP3;
      D5*AD5 = FWD5*A_FW + FTD15*AF1 + FTD25*AF2 + FTD35*AF3 + FTD45*AF4 +
FTD55*AF5 + FTD65*AF6 + FTD75*AF7 + TRPD5*ATRP_out + OR_out*AR_out;
      D6*AD6 = FWD6*A_FW + FTD16*AF1 + FTD26*AF2 + FTD36*AF3 + FTD46*AF4 +
FTD56*AF5 + FTD66*AF6 + FTD76*AF7 + TRPD6*ATRP_out + P5*AP5;
      D7*AD7 = FWD7*A_FW + FTD17*AF1 + FTD27*AF2 + FTD37*AF3 + FTD47*AF4 +
FTD57*AF5 + FTD67*AF6 + FTD77*AF7 + TRPD7*ATRP_out + P6*AP6;

[R33] AR_Out = 100;             !Reactor outlet temp from Cadsim;
      AP0 = 150;                !proper constraint (set by default);
      AP7 <= 70;                !proper constraint;


!TRP Balance;
TRP_In*ATRP_In = (TRP_Fil + TRP_Out)*ATRP_out;
      !INLET (Dilution TRP Balance) (DS);
      TRP_In*ATRP_In = FW_TRP*A_FW + (TRPF1*AF1 + TRPF2*AF2 + TRPF3*AF3 +
TRPF4*AF4 + TRPF5*AF5 + TRPF6*AF6 + TRPF7*AF7) + TRP_self_recy*ATRP_out +
P4*AP4;
      !Filtrate Balance (DS);
      TRP_Fil*ATRP_out = ((TRPS1 + TRPS2 + TRPS3 + TRPS4 + TRPS5 + TRPS6 +
TRPS7) + (TRPD1 + TRPD2 + TRPD3 + TRPD4 + TRPD5 + TRPD6 + TRPD7) +
TRP_self_recy)*ATRP_out;
      !Above redundant equation? Since ATRP_out same;
      ATRP_in = ATRP_out;                             !no heat loss across
TRP [assumption];

!=========================================================================;
!GASIFICATION SECTION;
!=========================================================================;
!Conversion Factors;
!1ST STAGE (per ton_pulp);
V_syn    = 1.688;

!V = mass conversion, VS = steam conversion, VE = elec conversion;
!2ND STAGE (per ton_pulp);
!Bio-product;
V_DMEa = 3.845e-2;
V_DMEb = 3.845e-2;
V_DMEc = 1.698e-2;
V_FTa  = 1.570e-2;
V_FTb  = 1.570e-2;
V_FTc  = 4.823e-3;
V_MA   = 9.299e-3;
```

```
!MP Steam;
VMPS_TOM    = 0.8928; !kg_MPst/ton_pulp;
VMPS_BLGCC  = 0.5474;
VMPS_DMEa   = 0.5474;
VMPS_DMEb   = 0.5474;
VMPS_DMEc   = 0.5474;
VMPS_FTa    = 0.5474;
VMPS_FTb    = 0.5474;
VMPS_FTc    = 0.5474;
[R44] VMPS_MA     = 0.5474;

!LP Steam;
VLPS_TOM    = 1.717; !kg_LPst/ton_pulp;
VLPS_BLGCC  = 1.067;
VLPS_DMEa   = 1.067;
VLPS_DMEb   = 1.067;
VLPS_DMEc   = 1.067;
VLPS_FTa    = 1.067;
VLPS_FTb    = 1.067;
VLPS_FTc    = 1.067;
VLPS_MA     = 1.067;

!Electricity;
VE_tom    = 4.537e-4; !MWh/ton_pulp;
VE_BLGCC = 5.274e-4;
VE_DMEa   = 2.589e-6*3.6e6;
VE_DMEb   = 4.061e-4;
VE_DMEc   = 4.185e-4;
VE_FTa    = 4.053e-4;
VE_FTb    = 1.058e-3;
VE_FTc    = 3.573e-4;
VE_MA     = 4.247e-4;

!==========================================================================;
!Mass Balance [feedstock];
!==========================================================================;
!Biomass feedstock/raw material (black liquor, kg_B/ton_pulp);
SBL = RM01 + RM02;

!==========================================================================;
!1ST STAGE PATHWAY (intermediate products);
!==========================================================================;
!Stage#01 Pathway#01 (TOM boiler);
ProdTOM_MPS    = RM01*VMPS_tom;       !kg_steam/ton_pulp;
ProdTOM_LPS    = RM01*VLPS_tom;       !kg_steam/ton_pulp;
ProdTOM_elec   = RM01*VE_tom;         !MWh/ton_pulp;

!Stage#01 Pathway#02 (Gasification);
ProdSYN        = RM02*V_syn;          !kg_syn/ton_pulp;
ProdSYN        = ProdSYN1 + ProdSYN2 + ProdSYN3 + ProdSYN4 + ProdSYN5 +
ProdSYN6 + ProdSYN7 + ProdSYN8;

!==========================================================================;
!2ND STAGE PATHWAY (final products);
!==========================================================================;
!Stage#02 Pathway#0201;
ProdBLGCC_MPS    = ProdSYN1*VMPS_BLGCC;     !kg_steam/ton_pulp;
ProdBLGCC_LPS    = ProdSYN1*VLPS_BLGCC;     !kg_steam/ton_pulp;
ProdBLGCC_elec   = ProdSYN1*VE_BLGCC;       !MWh/ton_pulp;
```

```
!Stage#02 Pathway#0202;
ProdDMEa         = ProdSYN2*V_DMEa;          !gal_DME/ton_pulp;
ProdDMEa_MPS     = ProdSYN2*VMPS_DMEa;       !kg_steam/ton_pulp;
ProdDMEa_LPS     = ProdSYN2*VLPS_DMEa;       !kg_steam/ton_pulp;
ProdDMEa_elec    = ProdSYN2*VE_DMEa;         !kJ/ton_pulp; !in kJ to solve
scaling issue;

!Stage#02 Pathway#0203;
ProdDMEb         = ProdSYN3*V_DMEb;          !gal_DME/ton_pulp;
ProdDMEb_MPS     = ProdSYN3*VMPS_DMEb;       !kg_steam/ton_pulp;
ProdDMEb_LPS     = ProdSYN3*VLPS_DMEb;       !kg_steam/ton_pulp;
ProdDMEb_elec    = ProdSYN3*VE_DMEb;         !MWh/ton_pulp;

!Stage#02 Pathway#0204;
ProdDMEc         = ProdSYN4*V_DMEc;          !gal_DME/ton_pulp;
ProdDMEc_MPS     = ProdSYN4*VMPS_DMEc;       !kg_steam/ton_pulp;
ProdDMEc_LPS     = ProdSYN4*VLPS_DMEc;       !kg_steam/ton_pulp;
ProdDMEc_elec    = ProdSYN4*VE_DMEc;         !MWh/ton_pulp;

!Stage#02 Pathway#0205;
ProdFTa          = ProdSYN5*V_FTa;           !gal_FT/ton_pulp;
ProdFTa_MPS      = ProdSYN5*VMPS_FTa;        !kg_steam/ton_pulp;
ProdFTa_LPS      = ProdSYN5*VLPS_FTa;        !kg_steam/ton_pulp;
ProdFTa_elec     = ProdSYN5*VE_FTa;          !MWh/ton_pulp;

!Stage#02 Pathway#0206;
ProdFTb          = ProdSYN6*V_FTb;           !gal_FT/ton_pulp;
ProdFTb_MPS      = ProdSYN6*VMPS_FTb;        !kg_steam/ton_pulp;
ProdFTb_LPS      = ProdSYN6*VLPS_FTb;        !kg_steam/ton_pulp;
ProdFTb_elec     = ProdSYN6*VE_FTb;          !MWh/ton_pulp;

!Stage#02 Pathway#0207;
ProdFTc          = ProdSYN7*V_FTc;           !gal_FT/ton_pulp;
ProdFTc_MPS      = ProdSYN7*VMPS_FTc;        !kg_steam/ton_pulp;
ProdFTc_LPS      = ProdSYN7*VLPS_FTc;        !kg_steam/ton_pulp;
ProdFTc_elec     = ProdSYN7*VE_FTc;          !MWh/ton_pulp;

!Stage#02 Pathway#0208;
ProdMA           = ProdSYN8*V_MA;      !gal_MA/ton_pulp;
ProdMA_MPS       = ProdSYN8*VMPS_MA;   !kg_steam/ton_pulp;
ProdMA_LPS       = ProdSYN8*VLPS_MA;   !kg_steam/ton_pulp;
ProdMA_elec      = ProdSYN8*VE_MA;     !MWh/ton_pulp;

!=========================================================================;
!Steam & Electricity Production;
!=========================================================================;
!Total Steam Production;
Total_MPS    = ProdTOM_MPS + ProdBLGCC_MPS + ProdDMEa_MPS + ProdDMEb_MPS +
ProdDMEc_MPS + ProdFTa_MPS + ProdFTb_MPS + ProdFTc_MPS + ProdMA_MPS;
      !kg_steam/ton_pulp;
Total_LPS    = ProdTOM_LPS + ProdBLGCC_LPS + ProdDMEa_LPS + ProdDMEb_LPS +
ProdDMEc_LPS + ProdFTa_LPS + ProdFTb_LPS + ProdFTc_LPS + ProdMA_LPS;
      !kg_steam/ton_pulp;

Total_st_sold      = LPS_sold + Total_MPS;        !kg_steam/ton_pulp;
Total_LPS          = LPS_sold + LPS_BSWS;         !kg/ton_pulp;
!Total_MPS         = MPS_sold + MPS_BSWS;         !kg/ton_pulp;
!Total_st          = Total_MPS + Total_LPS;       !kg_steam/ton_pulp;

!Total Electricity Production;
!Electricity generated is distributed to grid and pulp mill;
```

```
!1MWh = 3.6e6 kJ;
!1kJ  = 2.778e-7 MWh;
!Total_elec_kJ = Elec_grid + Elec_mill;                !kJ/ton_pulp;
Total_elec_MWh = ProdDMEa_elec/3.6e6 + Elec_MWh;       !MWh/ton_pulp;
Total_elec_kJ = ProdDMEa_elec + Elec_MWh*3.6e6;        !kJ/ton_pulp;
      Elec_MWh     = ProdTOM_elec + ProdBLGCC_elec + ProdDMEb_elec +
ProdDMEc_elec + ProdFTa_elec + ProdFTb_elec + ProdFTc_elec + ProdMA_elec;
!MWh/ton_pulp;
      !Elec_KJ     = ProdDMEa_elec;                    !kJ/ton_pulp;
      !Elec_MWh_kJ  = Elec_MWh*3.6e6;                  !kJ/ton_pulp;

END
```

Appendix 3: LINGO Model Formulation for Chapter 4

```
!==================================================;
!PULP & PAPER (PPM) BIOMASS;
!==================================================;
!Black Liquor; FB01 = 50;!39.37; !kg/s, Larson, Figure 6;
!Wood Residue; !FB02 = 7.12;  !kg/s, Larson, Figure 6;

!Splitting of flow rate;
FB01 = FB0101 + FB0102 + FB0103 + FB0104 + FB0105;    !kg/s;
!FB02 = FB0201 + FB0202 + FB0203 + FB0204 + FB0205;   !kg/s;

!==================================================;
!BIOENERGY BASED INDUSTRY;
!==================================================;
!Define Parameters;
!Boiler;
YP0101 = 0.8928;
YP0102 = 1.7170;
YP0103 = 1.6320;

!IGCC;
YP0201 = 0.9250;
YP0202 = 1.8007;
YP0203 = 3.2246;

!INDUSTRY_#1_BOILER (final product);
!MPS;        FP0101 = YP0101*FB0101; !kg/s;
!LPS;        FP0102 = YP0102*FB0101; !kg/s;
!ELEC;       FP0103 = YP0103*FB0101; !MW;

!INDUSTRY_#2_IGCC (final product);
!MPS;        FP0201 = YP0201*FB0102; !kg/s;
!LPS;        FP0202 = YP0202*FB0102; !kg/s;
!ELEC;       FP0203 = YP0203*FB0102; !MW;

!==================================================;
!BIOPRODUCT BASED INDUSTRY;
!==================================================;
!Define Parameters;
YP0301 = 0.0649; !gal DME/kg BL;
YP0401 = 0.0265; !gal FT/kg BL;
YP0501 = 0.0157; !gal MA/kg BL;

!YP0301 = 0.00491; !MM Btu/kg BL;
!YP0401 = 0.00318; !MM Btu/kg BL;
!YP0501 = 0.00175; !MM Btu/kg BL;

!YP0301 = 0.1663; !kg DME/kg BL;
!YP0401 = 0.0759; !kg FT/kg BL;
!YP0501 = 0.2305; !kg MA/kg BL;

!INDUSTRY_#3_DME_BIOREFINERY (final product);
!DME Final Product;      FP0301 = YP0301*FB0103; !gal DME/s;

!INDUSTRY_#3_FT_BIOREFINERY (final product);
!FT Final Product;       FP0401 = YP0401*FB0104; !gal FT/s;

!INDUSTRY_#3_MIXED_ALCOHOL_BIOREFINERY (final product);
!MA Final Product;       FP0501 = YP0501*FB0105; !gal MA/s;
```

```
!=================================================;
!ENERGY BALANCE;
!=================================================;
!Steam and power requirement of pulp & paper mill;
FMPS_PPM    = 35.14;    !kg MPS/s, Larson, Figure 6;
FLPS_PPM    = 67.60;    !kg LPS/s, Larson, Figure 6;
FELEC_PPM   = 60;!100.1;      !MW, Larson, Table 12;

!Power requirement of the three biorefinery players;
!FELEC_IND03 = 34.9;    !MW; !Larson Table 12 (DMEa);
!FELEC_IND04 = 31.8;    !MW; !Larson Table 12 (FTa);
!FELEC_IND05 = 41.6;    !MW; !Larson Table 12 (MA);

!=================================================;
!CONNECTIVITY;
!=================================================;
!-------------------------------------------------;
!Biomass links;
!-------------------------------------------------;
!Constraint on minimum biomass flow rate;
FB_MIN = 3; !kg/s;


FB0101/FB_MIN >= IB0101;      @BIN(IB0101);
FB0102/FB_MIN >= IB0102;      @BIN(IB0102);
FB0103/FB_MIN >= IB0103;      @BIN(IB0103);
FB0104/FB_MIN >= IB0104;      @BIN(IB0104);
FB0105/FB_MIN >= IB0105;      @BIN(IB0105);

!Constraint;
!If there is a connectance, biomass flow rate must be higher than FB_MIN,
else flow rate is set to 0;
FB0101 = @IF(IB0101 #EQ# 1, FB0101, 0);
FB0102 = @IF(IB0102 #EQ# 1, FB0102, 0);
FB0103 = @IF(IB0103 #EQ# 1, FB0103, 0);
FB0104 = @IF(IB0104 #EQ# 1, FB0104, 0);
FB0105 = @IF(IB0105 #EQ# 1, FB0105, 0);
!-------------------------------------------------;

!-------------------------------------------------;
!Steam (MPS and LPS) links;
!-------------------------------------------------;
![SINK] Steam balance at PPM (excess imported);
FMPS_PPM = FMPS_PPM01 + FMPS_PPM02 + FMPS_IMP;
FLPS_PPM = FLPS_PPM01 + FLPS_PPM02 + FLPS_IMP;

![SOURCE] MPS and LPS sent to PPM or exported;
!MPS boiler;       FP0101 = FMPS_PPM01 + FMPS_EXP01;
!MPS IGCC;         FP0201 = FMPS_PPM02 + FMPS_EXP02;
!LPS boiler;       FP0102 = FLPS_PPM01 + FLPS_EXP01;
!LPS IGCC;         FP0202 = FLPS_PPM02 + FLPS_EXP02;

!Minimum steam flow rate requirement;
!FMPS_MIN = 3;

!FLPS_MIN = 3;


!MPS/LPS links (original);
!Need to have biomass feed link to obtain by-product steam);
!FMPS_PPM01/FMPS_MIN >= IB0101;
```

```
!FMPS_PPM02/FMPS_MIN >= IB0102;
!FLPS_PPM01/FLPS_MIN >= IB0101;
!FLPS_PPM02/FLPS_MIN >= IB0102;

!MPS/LPS links (self-define);
!FMPS_PPM01/FMPS_MIN >= IMPS01;     !@BIN(IMPS01);
!FMPS_PPM02/FMPS_MIN >= IMPS02;     !@BIN(IMPS02);
!FLPS_PPM01/FLPS_MIN >= ILPS01;     !@BIN(ILPS01);
!FLPS_PPM02/FLPS_MIN >= ILPS02;     !@BIN(ILPS02);
!---------------------------------------------------;

!---------------------------------------------------;
!Power links;
!---------------------------------------------------;
![SINK] Power balance for each industry (excess imported);
FELEC_PPM   = FELEC_PPM01 + FELEC_PPM02 + FELEC_IMP_PPM;
FELEC_IND03 = FELEC_IND0301 + FELEC_IND0302 + FELEC_IMP_IND3;
FELEC_IND04 = FELEC_IND0401 + FELEC_IND0402 + FELEC_IMP_IND4;
FELEC_IND05 = FELEC_IND0501 + FELEC_IND0502 + FELEC_IMP_IND5;


!Minimum power flow rate requirement;
FELEC_MIN = 1;

![SOURCE] Elec sent to PPM or biorefinery;
!Elec boiler;     FP0103 = FELEC_PPM01 + FELEC_IND0301 + FELEC_IND0401 +
FELEC_IND0501 + FELEC_EXP_A;
!Elec IGCC;       FP0203 = FELEC_PPM02 + FELEC_IND0302 + FELEC_IND0402 +
FELEC_IND0502 + FELEC_EXP_B;

!Power requirement of the three biorefinery players;
FELEC_IND03 = @IF(IB0103 #EQ# 1, 34.9, 0);      !MW; !Larson Table 12
(DMEa);
FELEC_IND04 = @IF(IB0104 #EQ# 1, 31.8, 0);      !MW; !Larson Table 12
(FTa);
FELEC_IND05 = @IF(IB0105 #EQ# 1, 41.6, 0);      !MW; !Larson Table 12 (MA);

!Power links (original);
!FELEC_PPM01/FELEC_MIN >= IB0101;
!FELEC_PPM02/FELEC_MIN >= IB0102;
!FELEC_IND0301/FELEC_MIN >= IE0301;
!FELEC_IND0302/FELEC_MIN >= IE0302;
!FELEC_IND0401/FELEC_MIN >= IE0401;
!FELEC_IND0402/FELEC_MIN >= IE0402;
!FELEC_IND0501/FELEC_MIN >= IE0501;
!FELEC_IND0502/FELEC_MIN >= IE0502;

!Power links (self-define);
FELEC_PPM01/FELEC_MIN >= IEPPM01;         @BIN(IEPPM01);
FELEC_PPM02/FELEC_MIN >= IEPPM02;         @BIN(IEPPM02);
FELEC_IND0301/FELEC_MIN >= IE0301;        @BIN(IE0301);
FELEC_IND0302/FELEC_MIN >= IE0302;        @BIN(IE0302);
FELEC_IND0401/FELEC_MIN >= IE0401;        @BIN(IE0401);
FELEC_IND0402/FELEC_MIN >= IE0402;        @BIN(IE0402);
FELEC_IND0501/FELEC_MIN >= IE0501;        @BIN(IE0501);
FELEC_IND0502/FELEC_MIN >= IE0502;        @BIN(IE0502);

!Constraint; !If there is no biomass feed into I3, I4, I5, there should be
no linkage for power for I13, I14, I15, I23, I24, I25;
!i.e. limiting Le_Elec to a maximum of 2;
FELEC_IND0301 = @IF(IB0103 #EQ# 0, 0, FELEC_IND0301);
```

```
FELEC_IND0302 = @IF(IB0103 #EQ# 0, 0, FELEC_IND0302);
FELEC_IND0401 = @IF(IB0104 #EQ# 0, 0, FELEC_IND0401);
FELEC_IND0402 = @IF(IB0104 #EQ# 0, 0, FELEC_IND0402);
FELEC_IND0501 = @IF(IB0105 #EQ# 0, 0, FELEC_IND0501);
FELEC_IND0502 = @IF(IB0105 #EQ# 0, 0, FELEC_IND0502);
!--------------------------------------------------;

!--------------------------------------------------;
!Connectivity (Original);
!--------------------------------------------------;
!Objective Function;
!MAX  = Ce;

!Define connectivity index;
Ce     = Le/(S*(S-1)/2);

!Define number of industries;
S      = 6;

!Define total number of (potential) links;
Le     = Le_Biomass + Le_Elec;
      Le_Biomass  = IB0101 + IB0102 + IB0103 + IB0104 + IB0105;
      Le_Elec     = IE0301 + IE0302 + IE0401 + IE0402 + IE0501 + IE0502;

!--------------------------------------------------;
!Connectivity (Self-Define);
!--------------------------------------------------;
!Objective Function;
!MAX = Ce_self;

!Define connectivity index;
Ce_self = LeSD/Le_max;

!Define maximum number of links;
Le_max  = 15;

!Define total number of (potential) links;
LeSD   = Le_Biomass + Le_ElecSD;
      !Le_Steam   = IMPS01 + IMPS02 + ILPS01 + ILPS02;
      Le_ElecSD   = IEPPM01 + IEPPM02 + IE0301 + IE0302 + IE0401 + IE0402 +
IE0501 + IE0502;

Ce_selftest = LeSDtest/Le_max;
LeSDtest    = Le_Biomass;


!END
!==================================================;
!COSTING;
!==================================================;
!Define parameters;
i  = 0.10; !interest rate (0.10);
n  = 25;   !plant life;
CR = (i*(1+i)^n)/(((1+i)^n)-1); !capital recovery;
OT = 8330; !hr/y;
OH = 3600; !s/hr;

!Define Parameters;
YCAPEX_IND01 = 136e6;   !Boiler;
YCAPEX_IND02 = 218e6;   !IGCC;
YCAPEX_IND03 = 197e6;   !DME Biorefinery;
```

```
YCAPEX_IND04 = 170e6;    !FT Biorefinery;
YCAPEX_IND05 = 232e6;    !MA Biorefinery;

!Capital Expenditure;
TOTAL_CAPEX = CAPEX_IND01 + CAPEX_IND02 + CAPEX_IND03 + CAPEX_IND04 +
CAPEX_IND05; !$;
      CAPEX_IND01 = YCAPEX_IND01*IB0101;  !$;
      CAPEX_IND02 = YCAPEX_IND02*IB0102;  !$;
      CAPEX_IND03 = YCAPEX_IND03*IB0103;  !$;
      CAPEX_IND04 = YCAPEX_IND04*IB0104;  !$;
      CAPEX_IND05 = YCAPEX_IND05*IB0105;  !$;

!Annualized Capital Expenditure;
!ACAPEX = TOTAL_CAPEX*CR;

!Profitability;
PROFIT       = REV_STEAM + REV_ELEC + REV_PRODUCT;
            !$/y;
PROFIT2      = REV_STEAM + REV_ELEC + REV_PRODUCT - COST_STEAM - COST_ELEC;
            !$/y;

!Revenue;
REV_STEAM = REV_MPS + REV_LPS;
            !$/y;
      REV_MPS = ((FMPS_PPM01 + FMPS_PPM02)*SMPS_INT + (FMPS_EXP01 +
FMPS_EXP02)*SMPS_EXP)*OH*OT;        !$/y;
      REV_LPS = ((FLPS_PPM01 + FLPS_PPM02)*SLPS_INT + (FLPS_EXP01 +
FLPS_EXP02)*SLPS_EXP)*OH*OT;        !$/y;

      SMPS_INT = 0.0090;      !$/kg;
      SMPS_EXP = 0.0080;      !$/kg;
      SLPS_INT = 0.0060;      !$/kg;
      SLPS_EXP = 0.0050;      !$/kg;

REV_ELEC = REV_ELEC_BOI + REV_ELEC_IGCC + REV_ELEC_EXP;
            !$/y;
      REV_ELEC_BOI  = (FELEC_PPM01 + FELEC_IND0301 + FELEC_IND0401 +
FELEC_IND0501)*1000*SPELEC_INT*OT;  !$/y;
      REV_ELEC_IGCC = (FELEC_PPM02 + FELEC_IND0302 + FELEC_IND0402 +
FELEC_IND0502)*1000*SPELEC_INT*OT;  !$/y;
      REV_ELEC_EXP  = (FELEC_EXP_B + FELEC_EXP_A)*1000*SPELEC_EXP*OT;
                              !$/y;

      SPELEC_INT = 0.090;     !$/kWh;
      SPELEC_EXP = 0.080;     !$/kWh;

REV_PRODUCT = (FP0301*SP03 + FP0401*SP04 + FP0501*SP05)*OH*OT;
            !$/y;
      !REV_DME = FP0301*SP03*OT*OH;
      !REV_FT = FP0401*SP04*OT*OH;
      !REV_NA = FP0501*SP05*OT*OH;

      SP03 = 1.57;!1.10;      !$/gal;
      SP04 = 2.09;!1.54;      !$/gal;
      SP05 = 2.04;!1.77;      !$/gal;

      !SP03 = 14.7;           !$/MMBtu;
      !SP04 = 12.5;           !$/MMBtu;
      !SP05 = 16.0;           !$/MMBtu;

!Cost;
```

```
COST_STEAM = (FMPS_IMP*CMPS + FLPS_IMP*CLPS)*OH*OT;
            !$/y;
      CMPS = 0.0100;          !$/kg;
      CLPS = 0.0070;          !$/kg;

COST_ELEC = (FELEC_IMP_PPM + FELEC_IMP_IND3 + FELEC_IMP_IND4  +
FELEC_IMP_IND5)*1000*CELEC*OT;                  !$/y;
      CELEC = 0.100;          !$/kWh;

!Payback Period;
PP = TOTAL_CAPEX/PROFIT2;
PP <= 5;

!MAX = Ce;
MAX = Ce_self;

END
```

Appendix 4: Supporting Information for Chapter 6

Table A4.1. List of conversion factors in the proposed EIP

Enterprise	Conversion Factors					Reference
	Input	Output	Notation	Value	Unit	
Dissolving pulp mill (DPM) (c = 1)	Wood chips	Pulp	Y^{PULP}	0.450	t pulp/t chip	Larson, 2006 [100]
		Pre-hydrolyzate liquor	Y_b^{BIO} (b = 1)	0.038	t pre-hydrolyzate liquor/t chip	Montastruc, 2011 [129]
		Hog fuel	Y_b^{BIO} (b = 2)	0.180	t hog fuel/t chip	Larson, 2006 [100]
		Black liquor	Y_b^{BIO} (b = 3)	0.896	t black liquor/t chip	Larson, 2006 [100]
		Medium pressure steam	$Y_{c,s}^{SK}$ (c = 1, s = 3)	0.828	t MPS/t chip	Larson, 2006 [100]
		Low pressure steam	$Y_{j,s}^{SK}$ (c = 1, s = 4)	1.613	t LPS/t chip	Larson, 2006 [100]
		Electricity	Y_j^{EL} (c = 1)	706.8	kWh/t chip	Larson, 2006 [100]
Furfural biorefinery	Pre-hydrolyzate	Furfural	Y_b^{FUB} (b = 1)	0.55	t furfural/t pre-hydrolyzate liquor	Montastruc, 2011 [129]

(FUB) **(c = 2)**	liquor	Low pressure steam	$Y_{c,s}^{SK}$ (c = 2, s = 4)	3.933	t LPS/t pre-hydrolyzate liquor	Montastruc, 2011 [129]
		Electricity	Y_{c}^{EL} (c = 2)	220	kWh/t pre-hydrolyzate liquor	Montastruc, 2011 [129]
Gasification plant (GAS) **(c = 3)**	Black liquor	Syngas	Y_{b}^{SYN} (b = 3)	1.688	t syngas/t black liquor	Larson, 2006 [100]
		Electricity	Y_{c}^{EL} (c = 3)	198.7	kWh/t black liquor	Larson, 2006 [100]
Combined heat and power plant (CHP) **(c = 4)**	Black liquor	High pressure steam	$Y_{bs}^{SR\text{-}BOI}$ (b = 3, s = 2)	2.623	t HPS/t black liquor	Larson, 2006 [100]
	Hog fuel	High pressure steam	$Y_{bs}^{SR\text{-}BOI}$ (b = 2, s = 2)	3.132	t HPS/t hog fuel	Larson, 2006 [100]
	Syngas	Very high pressure steam	$Y_{s}^{SR\text{-}CC}$ (s = 1)	0.8255	t VHPS/t syngas	Larson, 2006 [100]
		Electricity	$Y^{EL\text{-}CC}$	407.30	kWh/t syngas	Larson, 2006

						[100]

Table A4.2. Steam turbine efficiency and specific enthalpy of steam in CHP

Parameters	Value	Unit	Reference
Steam turbine efficiency (η)	70	%	Assumption
Specific enthalpy (H_s) of:			
VHPS (117 bar, 535°C) (*s* = 1)	3445.4	MJ/t	Thermodynamic data
HPS (78.5 bar, 475°C) (*s* = 2)	3336.4	MJ/t	Thermodynamic data
MPS (13 bar, 192°C) (*s* = 3)	2786.5	MJ/t	Thermodynamic data
LPS (4.8 bar, 152°C) (*s* = 4)	2746.2	MJ/t	Thermodynamic data

Table A4.3. Prices of commodity in the proposed EIP

Material	Value ($/t)	Reference
Wood chips	150	
Pulp	750	
Pre-hydrolyzate liquor	50	
Hog fuel	15 (DPM) 20 (external)	
Black liquor	50	
Furfural	1500	Rafione, 2014 [113]
Syngas	65	
FTL (as diesel)	750	USD Price

Table A4.4. Energy prices in the proposed EIP

Energy/Utility	Value	Unit	Reference
MPS	10	USD/t	Hypothetical
LPS	6	USD/t	Hypothetical
Electricity (from grid)	0.15	USD/kWh	Hypothetical
Electricity (internally from CHP)	0.12	USD/kWh	Hypothetical
Electricity (to grid)	0.09	USD/kWh	Hypothetical

Table A4.5. Other economics data

Variables/Parameters	Value	Unit	Reference

Interest loan (i)	10	%	Assumption
Plant life (n)	20	y	Assumption
Annual operating time (AOT)	330	d/y	Assumption

Table A4.6. Enterprise plant base capacity and total capital investment

Enterprise	**Main output**	**Capacity, F_c^B (t/d)**	**Total capital investment, TCI_c^B (USD million)**	**Reference**
DPM	Pulp	4242	2500	
FUB	Furfural	34.5	26	Rafione, 2014 [113]
GAS	Syngas	5192	146*	Larson, 2006 [100]
FTL	FTL	233.28	60.67*	Larson, 2006 [100]
CHP (Tomlinson boiler) CHP (hog boiler)	HPS (s = 2)	8921.64 1926.72	167.42* 62.4*	Larson, 2006 [100]
CHP (combined cycle)	VHPS (s = 1)	2087520** (kWh/d)	109.73*	Larson, 2006 [100]

*TCI based on 2005 prices has been adjusted to 2014 prices using *Chemical Engineering Plant Index*.

**Primary output capacity of combined cycle in CHP is taken as electricity

Table A4.7. Projected annual cash flow of FUB at a discount rate (x) of 10%

End of year (y)	Total capital investment, TCI^{A}_{c} (USD million)	Revenue, REV_c (USD million)	Cost, $COST_c$ (USD million)	Net cash flow before tax, NCF^{B}_{c} (USD million)	Tax depreciation, TD_c (USD million)	Taxable income, TI_c (USD million)	Tax payment, TP_c (USD million)	Net cash flow after tax, NCF^{A}_{c} (USD million)	Discount factor, DF	Discounted cash flow, DCF_c (USD million)	Cumulative discounted cash flow, NPV_c (USD million)
1	43.8	0	0	-43.8	0	0	0	-43.8	0.91	-39.9	-39.9
2	0	28.6	3.5	25.1	2.2	22.9	6.9	18.2	0.83	15.1	-24.8
3	0	34.7	4.2	30.5	2.2	28.3	8.5	22.0	0.75	16.5	-8.2
4	0	40.8	5.0	35.9	2.2	33.7	10.1	25.8	0.68	17.6	9.4
5	0	40.8	5.0	35.9	2.2	33.7	10.1	25.8	0.62	16.0	25.4
6	0	40.8	5.0	35.9	2.2	33.7	10.1	25.8	0.56	14.6	39.9
7	0	40.8	5.0	35.9	2.2	33.7	10.1	25.8	0.51	13.2	53.2
8	0	40.8	5.0	35.9	2.2	33.7	10.1	25.8	0.47	12.0	65.2
9	0	40.8	5.0	35.9	2.2	33.7	10.1	25.8	0.42	10.9	76.1
10	0	40.8	5.0	35.9	2.2	33.7	10.1	25.8	0.39	9.9	86.1
11	0	40.8	5.0	35.9	2.2	33.7	10.1	25.8	0.35	9.0	95.1
12	0	40.8	5.0	35.9	2.2	33.7	10.1	25.8	0.32	8.2	103.3
13	0	40.8	5.0	35.9	2.2	33.7	10.1	25.8	0.29	7.5	110.8
14	0	40.8	5.0	35.9	2.2	33.7	10.1	25.8	0.26	6.8	117.6
15	0	40.8	5.0	35.9	2.2	33.7	10.1	25.8	0.24	6.2	123.7
16	0	40.8	5.0	35.9	2.2	33.7	10.1	25.8	0.22	5.6	129.3

17	0	40.8	5.0	35.9	2.2	33.7	10.1	25.8	0.20	5.1	134.4
18	0	40.8	5.0	35.9	2.2	33.7	10.1	25.8	0.18	4.6	139.1
19	0	40.8	5.0	35.9	2.2	33.7	10.1	25.8	0.16	4.2	143.3
20	0	40.8	5.0	35.9	2.2	33.7	10.1	25.8	0.15	3.8	147.1
21	0	40.8	5.0	35.9	2.2	33.7	10.1	25.8	0.14	3.5	150.6

Table A4.8. Projected annual cash flow of GAS at a discount rate (x) of 10%

End of year (y)	**Total capital investment, TCI^{A}_{c} (USD million)**	**Revenue, REV_c (USD million)**	**Cost, $COST_c$ (USD million)**	**Net cash flow before tax, NCF^{B}_{c} (USD million)**	**Tax depreciation, TD_c (USD million)**	**Taxable income, TI_c (USD million)**	**Tax payment, TP_c (USD million)**	**Net cash flow after tax, NCF^{A}_{c} (USD million)**	**Discount factor, DF**	**Discounted cash flow, DCF_c (USD million)**	**Cumulative discounted cash flow, NPV_c (USD million)**
1	160.0	0	0	-160.0	0	0	0	-160.0	0.91	-145.5	-145.5
2	0	90.8	61.1	29.7	8.00	21.7	6.5	23.2	0.83	19.2	-126.3
3	0	110.3	74.2	36.1	8.00	28.1	8.4	27.6	0.75	20.8	-105.5
4	0	129.7	87.3	42.4	8.00	34.4	10.3	32.1	0.68	21.9	-83.6
5	0	129.7	87.3	42.4	8.00	34.4	10.3	32.1	0.62	19.9	-63.7
6	0	129.7	87.3	42.4	8.00	34.4	10.3	32.1	0.56	18.1	-45.6
7	0	129.7	87.3	42.4	8.00	34.4	10.3	32.1	0.51	16.5	-29.1
8	0	129.7	87.3	42.4	8.00	34.4	10.3	32.1	0.47	15.0	-14.1
9	0	129.7	87.3	42.4	8.00	34.4	10.3	32.1	0.42	13.6	-0.5
10	0	129.7	87.3	42.4	8.00	34.4	10.3	32.1	0.39	12.4	11.8
11	0	129.7	87.3	42.4	8.00	34.4	10.3	32.1	0.35	11.2	23.1
12	0	129.7	87.3	42.4	8.00	34.4	10.3	32.1	0.32	10.2	33.3
13	0	129.7	87.3	42.4	8.00	34.4	10.3	32.1	0.29	9.3	42.6
14	0	129.7	87.3	42.4	8.00	34.4	10.3	32.1	0.26	8.5	51.1
15	0	129.7	87.3	42.4	8.00	34.4	10.3	32.1	0.24	7.7	58.7
16	0	129.7	87.3	42.4	8.00	34.4	10.3	32.1	0.22	7.0	65.7

17	0	129.7	87.3	42.4	8.00	34.4	10.3	32.1	0.20	6.3	72.1
18	0	129.7	87.3	42.4	8.00	34.4	10.3	32.1	0.18	5.8	77.8
19	0	129.7	87.3	42.4	8.00	34.4	10.3	32.1	0.16	5.2	83.1
20	0	129.7	87.3	42.4	8.00	34.4	10.3	32.1	0.15	4.8	87.9
21	0	129.7	87.3	42.4	8.00	34.4	10.3	32.1	0.14	4.3	92.2

Table A4.9. Projected annual cash flow of CHPH at a discount rate (x) of 10%

End of year (y)	Total capital investment, TCI^{A}_{c} (USD million)	Revenue, REV_c (USD million)	Cost, $COST_c$ (USD million)	Net cash flow before tax, NCF^{B}_{c} (USD million)	Tax depreciation, TD_c (USD million)	Taxable income, TI_c (USD million)	Tax payment, TP_c (USD million)	Net cash flow after tax, NCF^{A}_{c} (USD million)	Discount factor, DF	Discounted cash flow, DCF_c (USD million)	Cumulative discounted cash flow, NPV_c (USD million)
1	115.3	0	0	-115.3	0	0	0	-115.3	0.91	-104.8	-104.8
2	0	24.5	7.1	17.4	5.8	11.6	3.5	13.9	0.83	11.5	-93.3
3	0	29.7	8.6	21.1	5.8	15.4	4.6	16.5	0.75	12.4	-80.9
4	0	35.0	10.1	24.9	5.8	19.1	5.7	19.1	0.68	13.1	-67.8
5	0	35.0	10.1	24.9	5.8	19.1	5.7	19.1	0.62	11.9	-56.0
6	0	35.0	10.1	24.9	5.8	19.1	5.7	19.1	0.56	10.8	-45.2
7	0	35.0	10.1	24.9	5.8	19.1	5.7	19.1	0.51	9.8	-35.3
8	0	35.0	10.1	24.9	5.8	19.1	5.7	19.1	0.47	8.9	-26.4
9	0	35.0	10.1	24.9	5.8	19.1	5.7	19.1	0.42	8.1	-18.3
10	0	35.0	10.1	24.9	5.8	19.1	5.7	19.1	0.39	7.4	-10.9
11	0	35.0	10.1	24.9	5.8	19.1	5.7	19.1	0.35	6.7	-4.2
12	0	35.0	10.1	24.9	5.8	19.1	5.7	19.1	0.32	6.1	1.9
13	0	35.0	10.1	24.9	5.8	19.1	5.7	19.1	0.29	5.5	7.4
14	0	35.0	10.1	24.9	5.8	19.1	5.7	19.1	0.26	5.0	12.5
15	0	35.0	10.1	24.9	5.8	19.1	5.7	19.1	0.24	4.6	17.0
16	0	35.0	10.1	24.9	5.8	19.1	5.7	19.1	0.22	4.2	21.2

17	0	35.0	10.1	24.9	5.8	19.1	5.7	19.1	0.20	3.8	25.0
18	0	35.0	10.1	24.9	5.8	19.1	5.7	19.1	0.18	3.4	28.4
19	0	35.0	10.1	24.9	5.8	19.1	5.7	19.1	0.16	3.1	31.6
20	0	35.0	10.1	24.9	5.8	19.1	5.7	19.1	0.15	2.8	34.4
21	0	35.0	10.1	24.9	5.8	19.1	5.7	19.1	0.14	2.6	37.0

Table A4.10. Projected annual cash flow of CHPC at a discount rate (x) of 10%

End of year (y)	Total capital investment, TCI^{A}_{c} (USD million)	Revenue, REV_c (USD million)	Cost, $COST_c$ (USD million)	Net cash flow before tax, NCF^{B}_{c} (USD million)	Tax depreciation, TD_c (USD million)	Taxable income, TI_c (USD million)	Tax payment, TP_c (USD million)	Net cash flow after tax, NCF^{A}_{c} (USD million)	Discount factor, DF	Discounted cash flow, DCF_c (USD million)	Cumulative discounted cash flow, NPV_c (USD million)
1	121.2	0	0	-121.1	0	0	0	-121.2	0.91	-110.2	-110.2
2	0	95.3	90.8	4.4	6.1	-1.6	-0.5	4.9	0.83	4.1	-106.1
3	0	115.7	110.3	5.4	6.1	-0.7	-0.2	5.6	0.75	4.2	-101.9
4	0	136.1	130.0	6.4	6.1	0.3	0.1	6.3	0.68	4.3	-97.6
5	0	136.1	130.0	6.4	6.1	0.3	0.1	6.3	0.62	3.9	-93.7
6	0	136.1	130.0	6.4	6.1	0.3	0.1	6.3	0.56	3.5	-90.2
7	0	136.1	130.0	6.4	6.1	0.3	0.1	6.3	0.51	3.2	-87.0
8	0	136.1	130.0	6.4	6.1	0.3	0.1	6.3	0.47	2.9	-84.0
9	0	136.1	130.0	6.4	6.1	0.3	0.1	6.3	0.42	2.7	-81.4
10	0	136.1	130.0	6.4	6.1	0.3	0.1	6.3	0.39	2.4	-79.0
11	0	136.1	130.0	6.4	6.1	0.3	0.1	6.3	0.35	2.2	-76.8
12	0	136.1	130.0	6.4	6.1	0.3	0.1	6.3	0.32	2.0	-74.8
13	0	136.1	130.0	6.4	6.1	0.3	0.1	6.3	0.29	1.8	-73.0
14	0	136.1	130.0	6.4	6.1	0.3	0.1	6.3	0.26	1.6	-71.3
15	0	136.1	130.0	6.4	6.1	0.3	0.1	6.3	0.24	1.5	-69.8
16	0	136.1	130.0	6.4	6.1	0.3	0.1	6.3	0.22	1.4	-68.5

17	0	136.1	130.0	6.4	6.1	0.3	0.1	6.3	0.20	1.2	-67.2
18	0	136.1	130.0	6.4	6.1	0.3	0.1	6.3	0.18	1.1	-66.1
19	0	136.1	130.0	6.4	6.1	0.3	0.1	6.3	0.16	1.0	-65.1
20	0	136.1	130.0	6.4	6.1	0.3	0.1	6.3	0.15	0.9	-64.1
21	0	136.1	130.0	6.4	6.1	0.3	0.1	6.3	0.14	0.8	-63.3

Appendix 5: LINGO Model Formulation for Chapter 6

```
!===================================================;
!GAME THEORY (ERF) SCENARIO 1
!===================================================;

!===================================================;
!DISSOLVING PULP MILL [DPM]
!===================================================;
!Input Parameters;
F_CHIP       = 4000;      !t/d;
Y_MPS_DPM    = 0.8278;    !0.88;
Y_LPS_DPM    = 1.6128;    !1.69;
Y_EL_DPM     = 706.8;

!Output Parameters;
Y_PULP       = 0.45;
Y_PH         = 0.25*0.15;
Y_WR         = 0.18;
Y_BL         = 0.8957;    !0.78;

!Input/Utilities Flow;
E_MPS_DPM    = F_CHIP*Y_MPS_DPM;      !t/d;
E_LPS_DPM    = F_CHIP*Y_LPS_DPM;      !t/d;
E_EL_DPM     = F_CHIP*Y_EL_DPM;       !kWh/d;

!Output Flow;
F_PULP       = F_CHIP*Y_PULP;         !t/d;
F_PH         = F_CHIP*Y_PH;           !t/d;
F_WR         = F_CHIP*Y_WR;           !t/d;
F_WR         = F_WR_HOG + F_WR_SOLD;  !t/d;

F_BL         = F_CHIP*Y_BL;           !t/d;
F_BL         = F_BL_GAS + F_BL_BOI;   !t/d;

!===================================================;
!FURFURAL BIOREFINERY [FUB]
!===================================================;
!Parameters;
Y_LPS_FUB    = 3.933;!24.82;!3.933;
Y_EL_FUB     = 220;
Y_FUB        = 0.55;

!Input and Output Flow;
E_LPS_FUB    = F_PH*Y_LPS_FUB; !t/d;
E_EL_FUB     = F_PH*Y_EL_FUB;  !kWh/d;
F_FUB        = F_PH*Y_FUB;     !t/d;

!===================================================;
!GASIFICATION PLANT [GAS]
!===================================================;
!Parameters;
Y_EL_GAS = 198.7;
Y_SYN    = 1.688;

!Input and Output Flow;
E_EL_GAS     = F_BL_GAS*Y_EL_GAS;     !kWh/d;
F_SYN        = F_BL_GAS*Y_SYN;        !t/d;
F_SYN        = F_SYN_CC;              !t/d;
!F_SYN = F_SYN_FTL + F_SYN_CC;        !t/d;

!===================================================;
```

```
!CHP
!==================================================;
!Parameters;
Y_VHPS_BL    = 2.623;
Y_VHPS_WR    = 3.132;
Y_VVHPS_SYN = 0.8255; !0.6255;
Y_EL_SYN     = 407.30;
!F_WR_EXT    <= 1000;

!RECOVERY BOILER;
E_VHPS_TOM = F_BL_BOI*Y_VHPS_BL;                !t/d; !VHPS;

!POWER/HOG BOILER;
E_VHPS_HOG = (F_WR_HOG + F_WR_EXT)*Y_VHPS_WR;   !t/d; !VHPS;

!COMBINED CYCLE;
E_VVHPS_CC   = F_SYN_CC*Y_VVHPS_SYN;            !t/d; !VVHPS;
E_EL_CC      = F_SYN_CC*Y_EL_SYN;               !kWh/d;


!==================================================;
!OVERALL ENERGY BALANCE [SCA]
!==================================================;
!ENTHALPY;
H_VVHPS = 3445.4; !MJ/t;
H_VHPS  = 3336.4; !MJ/t; !3421.9;
H_MPS   = 2786.5; !MJ/t;
H_LPS   = 2746.2; !MJ/t;

!Turbine Efficiency;
n_t = 0.7;

!STEAM SOURCES;
F_SOURCE_VHPS_TOM = E_VHPS_TOM; !t/d;
F_SOURCE_VHPS_HOG = E_VHPS_HOG; !t/d;
F_SOURCE_VVHPS    = E_VVHPS_CC; !t/d;

!STEAM SOURCE BALANCE;
F_SOURCE_VHPS_TOM = F_SINK_MPS1D + F_SINK_LPS1D + F_SINK_LPS1F + F_COND1;
!t/d; !TOM;
F_SOURCE_VHPS_HOG = F_SINK_MPS2D + F_SINK_LPS2D + F_SINK_LPS2F + F_COND2;
!t/d; !HOG;
F_SOURCE_VVHPS    = F_SINK_MPS3D + F_SINK_LPS3D + F_SINK_LPS3F + F_COND3;
!t/d; !CC;

!STEAM SINK BALANCE;
F_SINK_MPS1D + F_SINK_MPS2D + F_SINK_MPS3D = E_MPS_DPM; !t/d;
F_SINK_LPS1D + F_SINK_LPS2D + F_SINK_LPS3D = E_LPS_DPM; !t/d;
F_SINK_LPS1F + F_SINK_LPS2F + F_SINK_LPS3F = E_LPS_FUB; !t/d;

TOTAL_SOURCE = F_SOURCE_VVHPS + F_SOURCE_VHPS_TOM + F_SOURCE_VHPS_HOG;
      !t/d;
TOTAL_SINK   = E_MPS_DPM + E_LPS_DPM + E_LPS_FUB;
      !t/d;

!ENERGY EXTRACTED;
!RECOVERY BOILER;
E_TOM_VHPMP = F_SOURCE_VHPS_TOM*(H_VHPS - H_MPS)*n_t;
      !MJ/d;
E_TOM_MPLP  = (F_SOURCE_VHPS_TOM - F_SINK_MPS1D)*(H_MPS - H_LPS)*n_t;
      !MJ/d;
```

```
!POWER/HOG BOILER;
E_HOG_VHPMP = F_SOURCE_VHPS_HOG*(H_VHPS - H_MPS)*n_t;
      !MJ/d;
E_HOG_MPLP  = (F_SOURCE_VHPS_HOG - F_SINK_MPS2D)*(H_MPS - H_LPS)*n_t;
      !MJ/d;

!COMBINED CYCLE;
E_CC_VVHPMP = F_SOURCE_VVHPS*(H_VVHPS - H_MPS)*n_t;
      !MJ/d;
E_CC_MPLP   =(F_SOURCE_VVHPS - F_SINK_MPS3D)*(H_MPS - H_LPS)*n_t;
      !MJ/d;

!ENERGY IN WATTS;
!RECOVERY/TOMLINSON BOILER;
POWER_TOM    = (E_TOM_VHPMP + E_TOM_MPLP)/3.6;    !kWh/d;
MW_TOM       = POWER_TOM*3.6/24/3600;             !MW;

!POWER/HOG BOILER;
POWER_HOG    = (E_HOG_VHPMP + E_HOG_MPLP)/3.6;    !kWh/d;
MW_HOG       = POWER_HOG*3.6/24/3600;             !MW;

!COMBINED CYCLE;
POWER_CC     = (E_CC_VVHPMP + E_CC_MPLP)/3.6 + E_EL_CC;      !kWh/d;
MW_CC        = POWER_CC*3.6/24/3600;                         !MW;

!TOTAL GENERATION;
POWER_INT = POWER_TOM + POWER_HOG + POWER_CC; !kWh/d;

POWER_TOM    = E_EL_INT_DPM1 + E_EL_INT_FUB1 + E_EL_INT_GAS1 + E_EL_EXP1;
!kWh/d;
POWER_HOG    = E_EL_INT_DPM2 + E_EL_INT_FUB2 + E_EL_INT_GAS2 + E_EL_EXP2;
!kWh/d;
POWER_CC     = E_EL_INT_DPM3 + E_EL_INT_FUB3 + E_EL_INT_GAS3 + E_EL_EXP3;
!kWh/d;

POWER_EXP    = E_EL_EXP1 + E_EL_EXP2 + E_EL_EXP3;      !kWh/d;

!TOTAL CONSUMPTION;
POWER_CON    = E_EL_DPM + E_EL_FUB + E_EL_GAS;                ! + E_EL_FTL;
      !kWh/d;
E_EL_DPM     = E_EL_INT_DPM1 + E_EL_INT_DPM2 + E_EL_INT_DPM3 + E_EL_EXT_DPM;
      !kWh/d;
E_EL_FUB     = E_EL_INT_FUB1 + E_EL_INT_FUB2 + E_EL_INT_FUB3 + E_EL_EXT_FUB;
      !kWh/d;
E_EL_GAS     = E_EL_INT_GAS1 + E_EL_INT_GAS2 + E_EL_INT_GAS3 + E_EL_EXT_GAS;
      !kWh/d;

!TOTAL EXTERNAL UTILITY;
POWER_EXT    = E_EL_EXT_DPM + E_EL_EXT_FUB + E_EL_EXT_GAS;! + E_EL_FTL_EXT;
!kWh/d;

!OVERALL BALANCE;
POWER_CON    = POWER_INT - POWER_EXP + POWER_EXT;      !kWh/d;

![REFERENCE];
MW_DPM       = E_EL_DPM*3.6/24/3600; !MW;
MW_FUB       = E_EL_FUB*3.6/24/3600; !MW;
MW_GAS       = E_EL_GAS*3.6/24/3600; !MW;

MW_CON       = POWER_CON*3.6/24/3600; !MW;
```

```
MW_INT       = POWER_INT*3.6/24/3600; !MW;
MW_EXT       = POWER_EXT*3.6/24/3600; !MW;
MW_EXP       = POWER_EXP*3.6/24/3600; !MW;

!RRATIO_TOM = (POWER_TOM*3.6)/((F_SINK_MPS1 + F_SINK_LPS1)*2500);
!RRATIO_HOG = (POWER_HOG*3.6)/((F_SINK_MPS2 + F_SINK_LPS2)*2500);
!RRATIO_CC  = (POWER_CC*3.6)/((F_SINK_MPS3 + F_SINK_LPS3)*2500);

!MIN = F_WR_EXT;
!MIN = MW_EXT;
!MIN = TOTAL_SOURCE;
!F_WR_EXT    <= 1000;


!==================================================;
!ECONOMICS
!==================================================;
!Material Price;
SP_CHIP      = 150;      !$/t  150-170 PDF;
SP_WR_DPM    = 15;       !$/t;
SP_WR_EXT    = 20;       !$/t  12-15 LARSON;
SP_WR_SOLD   = 10;       !$/t;
SP_PULP      = 700;      !$/t  500-750;
SP_BL        = 50;       !$/t;
SP_PH        = 50;       !$/t;
SP_FUB       = 1500;     !$/t  1200-1500;
SP_SYN       = 65;       !$/t;
!SP_FTL      = 750;      !$/t;
!F_BL_GAS = 0;
MAX = GP_Total;
!MAX = NPV_Total;
!MAX = GP_DPM;
!MAX = GP_FUB;
!MAX = GP_GAS;
!MAX = GP_CHPC;
!MIN = F_WR_EXT;
F_WR_EXT    <= 1000;
!Utility Price;
SP_MPS_INT   = SP_LPS_INT + 4;!15;   !$/t  4+4;
SP_LPS_INT   = 6;                    !$/t  4;
SP_EL_EXT    = SP_EL_INT + 0.03;     !$/kWh;
SP_EL_INT    = 0.12;     !$/kWh      0.10-0.12;
SP_EL_SOLD   = SP_EL_INT - 0.03;     !$/kWh;
!@FREE(SP_EL_SOLD);
!Parameter;
!capital recovery;       CR = (i*(1+i)^n)/(((1+i)^n)-1);
!interest;               i = 0.1;
!plant life;             n = 20;
!operating time;         AOT = 330;        !d/y;

!Free Variables;
@FREE(GP_DPM);
@FREE(GP_FUB);
@FREE(GP_GAS);
@FREE(GP_CHPT);
@FREE(GP_CHPH);
@FREE(GP_CHPC);
@FREE(GP_Total);

!--------------------------------------------------;
!Dissolving Pulp Mill;
```

```
!-------------------------------------------------;
!Profit, Revenue, Cost;
GP_DPM       = ((R_DPM - C_DPM)*AOT)/1e6 - ACC_DPM;          !M$/y;
R_DPM        = F_PULP*SP_PULP + (F_BL_GAS + F_BL_BOI)*SP_BL + F_PH*SP_PH +
F_WR_HOG*SP_WR_DPM + F_WR_SOLD*SP_WR_SOLD;       !$/d;
!R_DPM       = F_PULP*SP_PULP + F_PH*SP_PH + F_WR_SOLD*SP_WR_SOLD; !$/d;
C_DPM        = C_DPM_RM + C_DPM_MPS + C_DPM_LPS + C_DPM_EL;   !$/d;
      C_DPM_RM     = F_CHIP*SP_CHIP;                 !$/d;
      C_DPM_MPS    = (F_SINK_MPS1D + F_SINK_MPS2D +
F_SINK_MPS3D)*SP_MPS_INT;     !$/d;
      C_DPM_LPS    = (F_SINK_LPS1D + F_SINK_LPS2D +
F_SINK_LPS3D)*SP_LPS_INT;     !$/d;
      C_DPM_EL     = (E_EL_INT_DPM1 + E_EL_INT_DPM2 +
E_EL_INT_DPM3)*SP_EL_INT + E_EL_EXT_DPM*SP_EL_EXT;     !$/d;

!Annualized Investment Cost;
YCC_DPM      = 1500;                             !$/(t/y);
CC_DPM       = (F_PULP*AOT*YCC_DPM)/1e6;         !M$;
!!!!CC_DPM2        = 2500*(F_PULP*AOT/1.4e6)^0.6;      !M$;
ACC_DPM      = CC_DPM*CR;                        !M$/y;

!MAX = GP_DPM;
!END
!-------------------------------------------------;
!Furfural Biorefinery;
!-------------------------------------------------;
!Profit, Revenue, Cost;
GP_FUB       = ((R_FUB - C_FUB)*AOT)/1e6 - ACC_FUB;     !M$/y;
R_FUB        = F_FUB*SP_FUB;                            !$/d;
C_FUB        = C_FUB_RM + C_FUB_LPS + C_FUB_EL;         !$/d;
      C_FUB_RM     = F_PH*SP_PH;                    !$/d;
      C_FUB_LPS    = (F_SINK_LPS1F + F_SINK_LPS2F +
F_SINK_LPS3F)*SP_LPS_INT;     !$/d;
      C_FUB_EL     = (E_EL_INT_FUB1 + E_EL_INT_FUB2 +
E_EL_INT_FUB3)*SP_EL_INT + E_EL_EXT_FUB*SP_EL_EXT;      !$/d;

!Annualized Investment Cost;
F_FUB_Annual = F_FUB*AOT;                        !t/y;
CC_FUB         = 26*(F_FUB_Annual/11400)^0.6;    !M$;
ACC_FUB        = CC_FUB*CR;                      !M$/y;

!MAX = GP_FUB;
!END
!-------------------------------------------------;
!Gasification Plant;
!-------------------------------------------------;
!Profit, Revenue, Cost;
GP_GAS       = ((R_GAS - C_GAS)*AOT)/1e6 - ACC_GAS;     !M$/y;
!R_GAS       = (F_SYN_FTL + F_SYN_CC)*SP_SYN;           !$/d;
R_GAS        = (F_SYN_CC)*SP_SYN;                       !$/d;
C_GAS        = C_GAS_RM + C_GAS_EL;                     !$/d;
      C_GAS_RM     = F_BL_GAS*SP_BL;                    !$/d;
      C_GAS_EL     = (E_EL_INT_GAS1 + E_EL_INT_GAS2 +
E_EL_INT_GAS3)*SP_EL_INT + E_EL_EXT_GAS*SP_EL_EXT;      !$/d;

!Annualized Investment Cost;
CC_GAS       = 146*(F_SYN/5192.64)^0.6;     !M$;
ACC_GAS      = CC_GAS*CR;                   !M$/y;

!MAX = GP_GAS;
!END
```

```
!---------------------------------------------------;
!Combined Heat and Power Plant (Tomlinson);
!---------------------------------------------------;
!Profit, Revenue, Cost;
GP_CHPT      = ((R_CHPT - C_CHPT)*AOT)/1e6 - ACC_CHPT; !M$/y;
R_CHPT       = R_CHPT_MPS + R_CHPT_LPS + R_CHPT_EL;     !$/d;
      R_CHPT_MPS  = F_SINK_MPS1D*SP_MPS_INT;          !$/d;
      R_CHPT_LPS  = (F_SINK_LPS1D + F_SINK_LPS1F)*SP_LPS_INT;
      !$/d;
      R_CHPT_EL   = (E_EL_INT_DPM1 + E_EL_INT_FUB1 +
E_EL_INT_GAS1)*SP_EL_INT + E_EL_EXP1*SP_EL_SOLD; !$/d;
C_CHPT       = F_BL_BOI*SP_BL; !$/d;

!Annualized Investment Cost;
CC_CHPT      = 167.42*(E_VHPS_TOM/8921.64)^0.6;  !M$;
ACC_CHPT     = CC_CHPT*CR; !M$/y;

!MAX = GP_CHPT;
!END
!---------------------------------------------------;
!Combined Heat and Power Plant (Hog);
!---------------------------------------------------;
!Profit, Revenue, Cost;
GP_CHPH      = ((R_CHPH - C_CHPH)*AOT)/1e6 - ACC_CHPH; !M$/y;
R_CHPH       = R_CHPH_MPS + R_CHPH_LPS + R_CHPH_EL;     !$/d;
      R_CHPH_MPS  = F_SINK_MPS2D*SP_MPS_INT;          !$/d;
      R_CHPH_LPS  = (F_SINK_LPS2D + F_SINK_LPS2F)*SP_LPS_INT;
      !$/d;
      R_CHPH_EL   = (E_EL_INT_DPM2 + E_EL_INT_FUB2 +
E_EL_INT_GAS2)*SP_EL_INT + E_EL_EXP2*SP_EL_SOLD; !$/d;
C_CHPH       = F_WR_HOG*SP_WR_DPM + F_WR_EXT*SP_WR_EXT; !$/d;
!C_CHPH      = F_WR_EXT*SP_WR_EXT; !$/d;

!Annualized Investment Cost;
CC_CHPH      = 62.4*(E_VHPS_HOG/1926.72)^0.6;    !M$;
ACC_CHPH     = CC_CHPH*CR; !M$/y;

!MAX = GP_CHPH;
!END
!---------------------------------------------------;
!Combined Heat and Power Plant (CC);
!---------------------------------------------------;
!Profit, Revenue, Cost;
GP_CHPC      = ((R_CHPC - C_CHPC)*AOT)/1e6 - ACC_CHPC; !M$/y;
R_CHPC       = R_CHPC_MPS + R_CHPC_LPS + R_CHPC_EL;     !$/d;
      R_CHPC_MPS  = F_SINK_MPS3D*SP_MPS_INT;          !$/d;
      R_CHPC_LPS  = (F_SINK_LPS3D + F_SINK_LPS3F)*SP_LPS_INT;
      !$/d;
      R_CHPC_EL   = (E_EL_INT_DPM3 + E_EL_INT_FUB3 +
E_EL_INT_GAS3)*SP_EL_INT + E_EL_EXP3*SP_EL_SOLD;
C_CHPC       = F_SYN_CC*SP_SYN;      !$/d;

!Annualized Investment Cost;
CC_CHPC      = 109.73*(E_EL_CC/2087520)^0.6;     !M$; !2793402;
ACC_CHPC     = CC_CHPC*CR;                 !M$/y;

!MAX = GP_CHPC;
!END
!---------------------------------------------------;
!Overall Profit;
!---------------------------------------------------;
```

```
GP_Total = GP_DPM + GP_FUB + GP_GAS + GP_CHPT + GP_CHPH + GP_CHPC ;!+
GP_FTL;
END
```