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Total Site Heat and Mass Integration and Optimisation using P-graph: A Biorefinery Case Study

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The aim of this paper is to solve total site heat and mass integration and optimisation using P-graph framework, with a biorefinery case study. Total site heat and mass integration is important for the selection of biorefinery processes because it must achieve high material and energy efficiency to be economically competitive. This paper considers co-location of simultaneous scarification and co-fermentation of wood, hydrothermal liquefaction of forest residues and gasification of black liquor with an existing Kraft pulp mill in Central North Island of New Zealand. Result shows that the Kraft pulp mill is the most profitable biorefinery option, followed by hydrothermal liquefaction. However, an increment in the price of bio-oil by 5 % puts hydrothermal liquefaction in the optimal network with Kraft pulp mill.

1. Introduction

Forestry is an important industry in New Zealand. The forestry sector is the third largest export earner, exporting logs, pulp and paper and other residues. The wood is bulk processed in New Zealand and is made into a wide range of traditional wood products such as sawn lumber, pulp and paper products, and medium density fibre board. In addition to domestic processing, a large proportion of logs are exported as whole logs. Increased competition and volatile foreign exchange rate affect the forestry industry in New Zealand and drive the industry to look into other opportunities to diversify the product to generate extra revenues and profits from the same quantum of wood feedstock. In principle, co-location of biorefineries with existing pulp mills allows the potential for highly integrated and efficient production of multiple products by fully utilising material and energy inputs and re-using waste materials. There are a number of promising emerging secondary processing technologies that could use wood residues to produce high value bio-based fuels and chemical for rapidly growing markets (de Jong et al., 2012).

Integration of new processes with existing processes should be implemented to assist both the economics and environmental footprint of the new processes and products (Čuček et al., 2015). By implementing an integrated biorefinery concept, the material and energy demand profiles of the processing cluster changes (Marinova et al., 2009). The selection of new products and processes includes, therefore, a multi-dimensional – material and energy – optimisation. Lundberg et al. (2014) showed that with increased heat integration, both dissolving pulp and hemicellulose extraction processes could be added to an existing Swedish Kraft pulp mill while maintaining a steam surplus that could be used for additional upgrading processes or electricity production.

Process Integration (PI) is a holistic approach to design operation which emphasises the unity of the process (El-Halwagi, 1997). One important PI method is Total Site Heat Integration (TSHI). TSHI integrates a number of individual processes to recover heat indirectly via a common utility system, which offers additional inter-process heat recovery (HR) through consumption and generation of utilities (Klemeš, 2013). By carrying out TSHI, the heat profiles of each individual processes are identified to represent the site utility systems for utility targeting. It then can be used to analyse and make changes to the utility system to improve the total site heat integration through the utility system. Possible changes might include: (i) replacing steam by introducing hot water to lower

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temperature processes; (ii) introducing new steam levels that can be generated from recovered process heat at higher levels and/ or process stream heating with steam at lower levels; and (iii) introducing new renewable energy processes, such as geothermal heat or power.

One promising framework to undertake biorefinery optimisation studies is the Process Graph framework. Process Graph or P-graph is a bipartite graph that uses a combinatorial optimisation framework to optimise process network synthesis (PNS) problems. P-graph is more advantageous than mathematical programming (MP) as it solves PNS problems through the combinatorial nature of the problem instead of translating the problem into sets of equations. The combinatorial instrument, the five P-graph axioms and P-graph algorithm, which was initially proposed by (Friedler et al., 1992). One of the key advantages of P-graph is P-graph generates optimal and near-optimal flowsheets for further analysis. The P-graph methodology has been extended to solve problems such as optimisation of regional supply chains (Lam et al., 2010), heat exchanger network synthesis (Nagy et al., 2001) and efficient energy conversion networks using fuel cells (Varbanov and Friedler, 2008). The addition of energy into P-graph has been simplified. The thermal energy stream added doesn't take into account the steam conditions. Klemeš and Varbanov (2015) mentioned that the application of Process Integration in P-graph has not been fully exploited. To date, optimisation of a PNS problem with varying degree qualities of heat hasn't been reported. The aim of this paper is to use P-graph framework to solve a Total Site Heat Integration problem. The case study of the paper is to optimise the selection and production rates of a multi-process biorefinery using a combined heat and mass integration approach in P-graph. The scope of the considered biorefinery processes in this study has been limited to gasification of black liquor (BL), hydrothermal liquefaction (HTL) of biomass and simultaneous scarification and co-fermentation (SSCF) of biomass. To achieve this aim, a Pinch Analysis study of each considered biorefinery process is undertaken. Material and energy demand information for each process is co-located with an existing Kraft Pulp Mill to create a P-graph superstructure for the biorefinery. This superstructure consists of the possibility of material integration between biorefinery processes as well as Total Site Heat Integration through a common steam and hot water utility system.

2. Methodology

2.1 Mass and Energy Balance

The studied Kraft pulp mill is based on an existing Kraft pulp mill in Central North Island of New Zealand. The process data and conditions for gasification are extracted from Larson et al. (2006); HTL is from Zhu et al. (2014) for mass balance and Tews et al. (2014) for process data; the process data of SSCF is from Aden et al. (2002) and the mass balance for SSCF is extracted from Arvidsson and Lundin (2011). Mass and energy balances are then calculated in an Excel™ spreadsheet and process heating and cooling demands summarised in the form of stream data.

2.2 Process Integration

With the thermal data extracted, pinch analysis is carried out to provide the target for minimum energy consumption. The Grand Composite Curve is the constructed to allow targeting of multiple utility levels. This is carried out in an Excel™ spreadsheet. By applying the method, Heat Recovery, and required hot and cold utilities will be targeted for the Total Site problem. These data are inputted in P-graph and optimised using the P-graph framework.

2.3 P-graph

For this paper, the P-graph methodology is used to select the biorefinery process and its production rates. Piece-wise linear approximation (Ong et al., 2016) is included for raw materials and operating units. P-graph uses fixed investments costs plus a linear function of plant size that is proportional to input material flow rates. However, capital costs estimation normally requires a non-linear function. Capital costs are estimated by summing individual costs and applying factors when sufficient data are available. When data is not sufficient, the capital cost for the different capacities of the biorefinery processes are estimated with the rule of six-tenths which is given as:

$$CC_B = kS_B{}^a \tag{1}$$

where CC_B is the approximate cost of the process with a capacity S_B, a is the scale component and k is a constant of the nominal cost of the process at unit scale.

For the raw material, the cost of delivered wood biomass is also non-linear, being governed by available volume and distance. Higher required wood volumes increase the average distance travelled from harvest source to industrial site and therefore the delivered cost of biomass to the site.

2.4 Sensitivity Analysis

Slight changes in feedstock cost, product price, operational and capital costs can cause major changes to the feasible structures. As a result, a sensitivity analysis is carried out by altering the costs of the products by ± 5 %.

3. Case Study

The case study considered in this paper is a wood-to-fuel biorefinery, co-locating with an existing Kraft Pulp Mill. The raw material is wood biomass with dimethyl-ether (DME), bio-oil and ethanol as potential products. The processes considered in this case are gasification of black liquor, HTL of biomass and SSCF of biomass with a combined heat and power (CHP) on site, as shown in Figure 1.

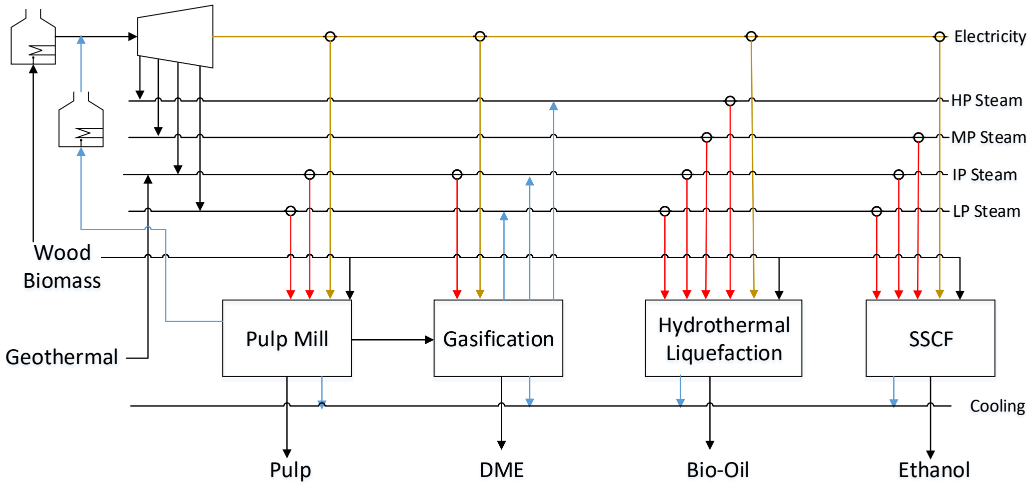

Figure 1: Total Site of the biorefinery considered for the case study.

The process stream data are collected from a Kraft pulp mill in the Central North Island of New Zealand. The turbine model in the CHP is assumed to have an isentropic efficiency of 70 %. The steam entering turbine is at 120 bar and 540 °C. The steam conditions for each header are presented in Table 1.

Table 1: Parameters of the steam level.

	High Pressure (HP) Steam	Medium Pressure (MP) Steam	Intermediate Pressure (IP) Steam	Low Pressure (LP) Steam
Pressure (bar)	40	20	13	4
Temperature (°C)	390	310	230	170

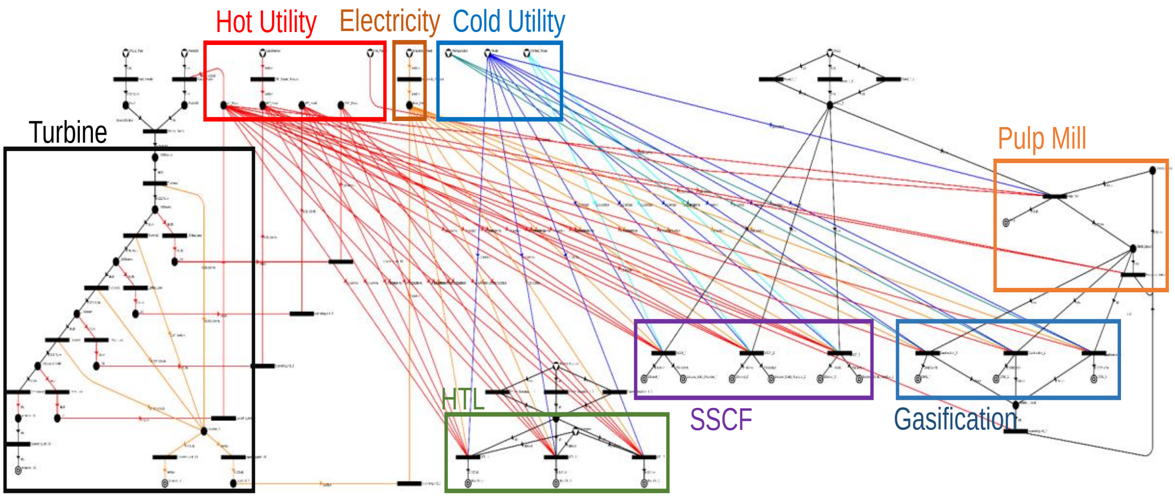

Figure 2: Maximal structure of the P-graph for the biorefinery processing of forest biomass residues.

Cost data and conversion rates were gathered from a variety of sources including published literature and design reports. Product price information was based on historical average data. Table 2 shows the derived power law equation of the three biorefinery processes for the non-linear approximation (Ong et al. 2016). The lower and upper bound are proportional to input flow rate in t/h. Process integration analysis is then conducted for the processes to determine the utilities required. The maximal structure for P-graph is shown in Figure 2.

Table 2: Derived power law equation of the processes for non-linear approximation.

Processes	k ($/[t/h]^n)	a	Lower Multiplier Capacity (t/h)	Upper Multiplier Capacity (t/h)
SSCF	9,119,300	0.63	30.0	53.0
HTL	11,339,800	0.60	130.0	210.0
Gasification	25,827,700	0.60	80.0	125.0

4. Results and Discussion

The advantage of this method is to have a better modelling of the turbine. In the current case, turbine model is assumed to have a constant isentropic efficiency. However, the efficiency of the turbine model is affected by the flow rate of steam. By knowing the conditions of the steam extracted at different levels improves the accuracy of the power generation estimates as well as the cost estimate.

4.1 Process Integration

Figure 3 shows the Grand Composite Curves of (a) SSCF, (b) hydrothermal liquefaction, (c) gasification and (d) Kraft pulp mill. These data are then included in P-graphs.

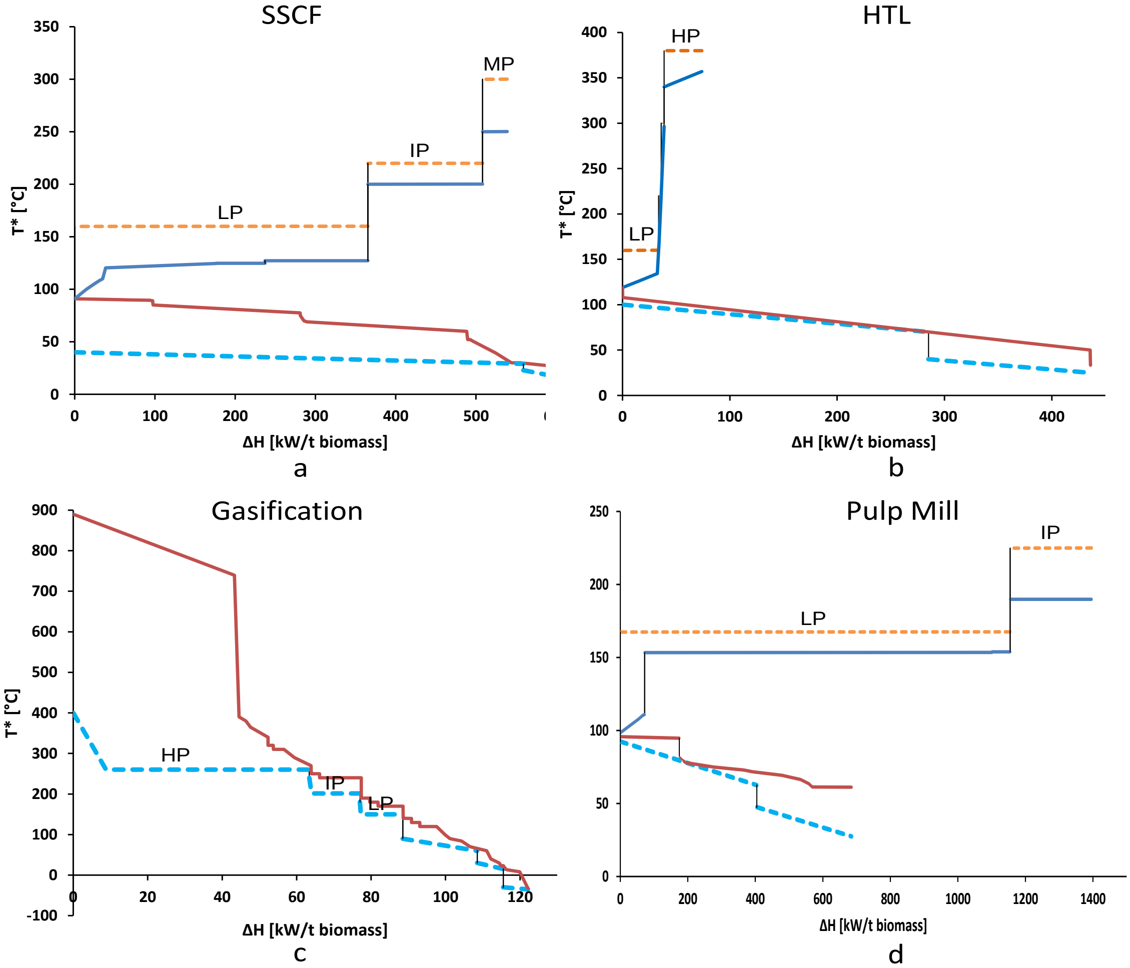

Figure 3: Grand Composite Curves for (a) simultaneous scarification and co-fermentation of pine, (b) hydrothermal liquefaction of forest residues, (c) gasification of black liquor and (d) Kraft pulp mill.

By carrying out process integration for each of the processes, conditions of steam used or generated through heat recovery by the processes is identified. It reduces the cost of utilities because intermediate utilities can be introduced and allows the introduction of renewable energy at the appropriate conditions to avoid temperature cross and lower heat recovery. In this case study, geothermal is introduced as IP steam.

4.2 P-graph

The optimal network, the solution with the greatest yearly profit, is shown in Figure 4 and indicates only Kraft pulp is produced at 600,000 t/y with a yearly profit of $ 45,456,000. In the second sub-optimal processing route bio-oil is produced along with Kraft pulp at 219,200 t/y through hydrothermal liquefaction of forest residue.

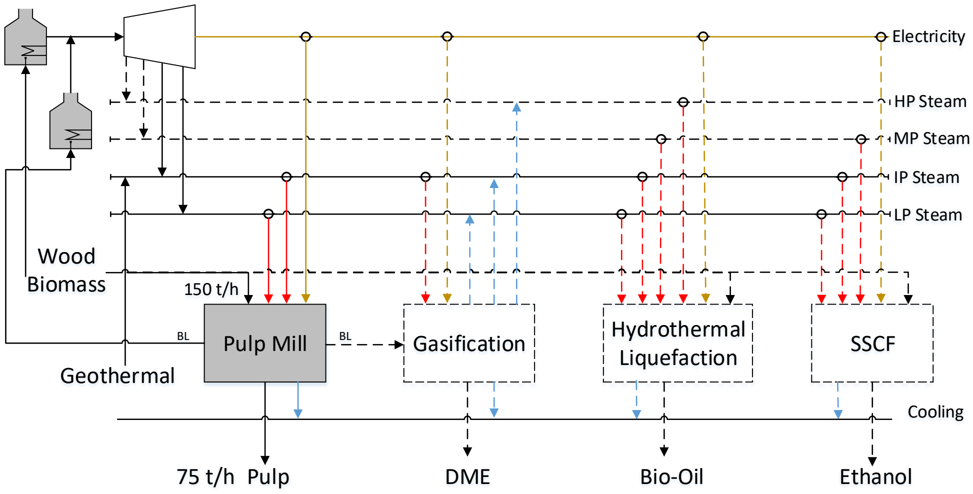

Figure 4: Optimal network showing Kraft pulp as the most profitable processing route.

4.3 Sensitivity Analysis

The cost of biorefinery products, DME, bio-oil and ethanol are changed by ± 5 %. Biorefinery options routes were not considered in any feasible solutions when the cost of the products was decreased by 5 %. When the prices of the products are increased by 5 %, pulp is produced at the same rate with production rate of bio-oil at 219,200 t/y with a yearly profit of $ 45,776,000. The second sub-optimal network in the earlier case is now the optimal network.

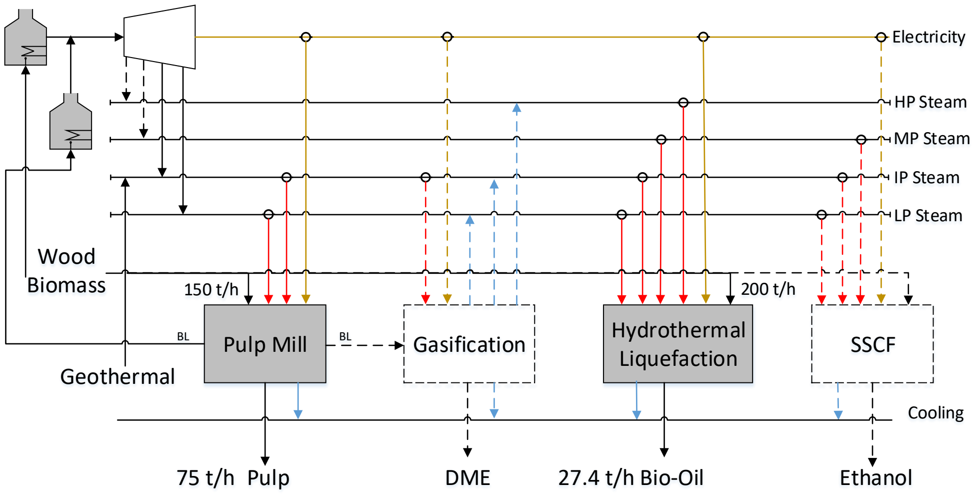

Figure 5: Optimal network with + 5 % increment in biorefinery product prices.

5. Conclusion

The P-graph framework has been used to solve a total site heat integration problem with two-step optimisation methodology. In general, P-graph has successfully solved numerous PNS problems. The cost benefit of carrying out process integration, in terms of capital and operating costs of utilities, have been proven to be profitable for both designs of new plants and retrofitting. Hence, solving a PNS problem without consideration of thermal energy, including steam conditions, may omit the opportunities for possible processing routes to be feasible. In this paper, combination of pulp mill and hydrothermal liquefaction present as profitable. Future work will be on analysing the co-location of hydrothermal liquefaction with Kraft pulp mill, but with black liquor as an additional feedstock.

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