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Application of P-graph Techniques for Efficient use of Wood Processing Residues in Biorefineries

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It is anticipated that demand for chemicals and fuel derived from sustainably grown bio-mass will increase over the coming decades. Forest and wood processing residues and waste are likely to become a significant feedstock to large scale biorefineries to produce both renewable fuels and chemicals. Maximising the economic value of these residues whilst simultaneously minimising the environmental impact of the manufactured product is an important task in process and product selection and design. Multiple processing and product pathways exist and it is often unclear what the best options are without detailed assessment or preliminary design. The P-graph framework was used to examine the economically feasibility of utilising five types of wood processing residues: wood chip, pulp logs, saw dust, and landing and cutover residues. Twenty different products were considered, based on three main production platforms or routes, sugars, pyrolysis, and gasification. Kraft pulp production and energy products were also considered as viable options for residues. Only six of the products considered were found to be profitable with the most economically viable uses being kraft pulp production and boiler fuel. Products included in the feasible solutions and the source of residues are all finely balanced, and slight changes in feedstock cost, product price, and operational and capital costs can cause major changes to the feasible structures. When heat integration for using Total Site was incorporated into the P-graph there was no economic benefit for the routes and scale of production considered here.

1. Introduction

The efficient use of woody biomass is essential for an economically viable forestry and wood processing industry. Traditionally logs were harvested with the principal part of the log going to primary processors, such as saw mills, while the top log or pulp log would go to secondary processors, such as pulp and fibreboard mills. Unconverted biomass from primary processors would also be transferred to secondary processors or used for fuel. Forestry residues also exist, although they are typically underutilised and not suitable for many traditional secondary processes, they may be suitable as a feedstock to future biorefineries. However, underutilisation of processing and forestry residues should not be mistaken for limitless supply, as there is a finite economic quantity available to a given plant. Forest location and therefore biomass transportation have a major effect on delivered biomass quantity and cost. Biorefineries are plants where biomass is transformed into several value-added products, such as fuels or chemicals (Browne et al., 2013), and may often be part of a larger industrial cluster (Atkins et al., 2016). The economics of biorefineries are reliant on optimising the use of these forest and processing residues and economically producing value-added fuels and chemicals, many of which are still in the developmental or pre-commercial stages. The selection of economic optimum processing routes is therefore an important process synthesis challenge.
The aim of this paper is to investigate economic processing routes using available quantities of processing and forestry residues at a location in the Central North Island of New Zealand. Selected products and processes were examined using a P-graph approach, with the required data (i.e. processing conversion rates and capex and opex costings) was taken from literature and NZ based values. Products that have established markets (e.g. wood pellets) and emerging/potential markets (e.g. bio-butanol) were considered.

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2. P-graph

P-graph framework (or process graph) is graph-theoretic approach to process synthesis based on rigorous and robust axioms and algorithms developed by Friedler and Fan (Friedler et al, 1995). The graphical representation of the numerous process networks or pathways is unambiguous and the problem formulation and LP solver algorithm of P-graph of allows for complex problems to be optimised very efficiently. Numerous different applications of P-graph have been published over the past two decades, with many examining the use of grains to produce fuels and chemicals (Liu et al., 2004), optimal synthesis of open-structure biomass networks (Lam et al. 2012), renewable resource utilisation for a green biorefinery (Halasz et al., 2005), supply-chain and processing of underutilised biomass into fuels and chemicals in Malaysia (How et al., 2015) and optimisation of industrial symbiotic networks (Aviso, 2015).

3. Processes and products

P-Graph Studio 4.0.5.0 was used to generate the P-graph structure and also to solve the synthesis problem. Cost data and conversion rates were gathered from a variety of sources including published literature, design reports and the author's own data. Product price information was based on historical average data and for products with limited or no current market size, predicted future prices and market size potentials were used. Intermediate processing steps for biomass size reduction (e.g. chipping of pulp logs) were included where required. Transportation costs of biomass were also included as a separate operating unit in the P-graph.
The maximal structure for the P-graph is shown in Figure 1, with feedstocks at the top (solid circle with white triangle) and products at the bottom (two concentric circles). Intermediate materials are indicated with a solid circle and operating units as a solid horizontal bar.

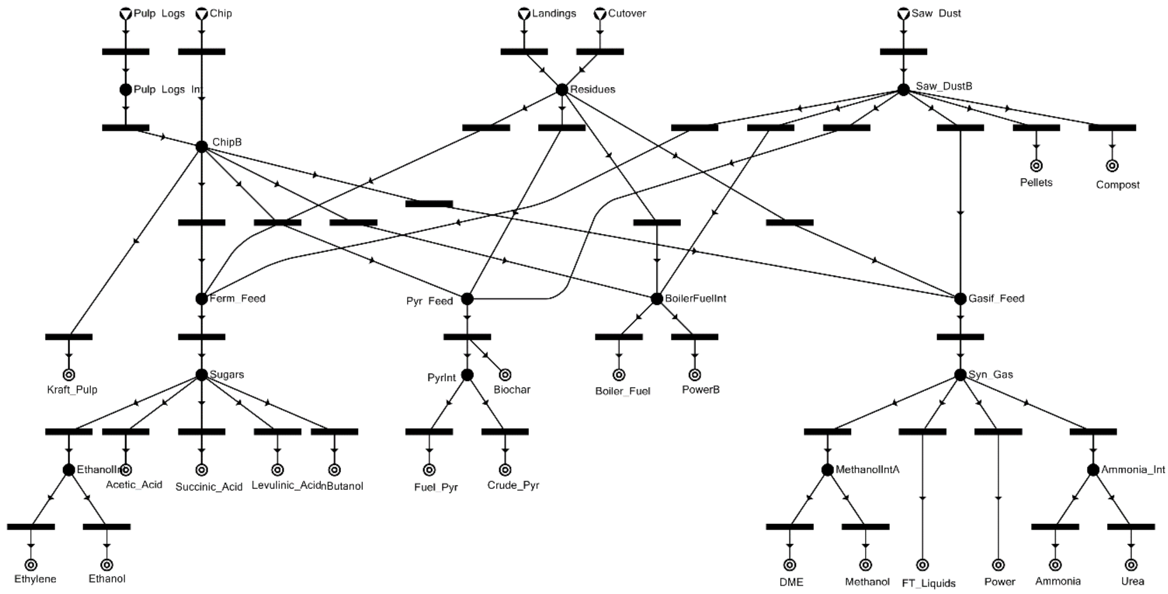

Figure 1: Maximal structure of the P-graph for the processing of process and forest biomass residues

The wood processing residues availability and delivered cost data are based on representative values for a central location in the Central North Island of New Zealand. All biomass is considered on a dry basis. Typical moisture contents for the several feedstocks have been used to convert cost and conversion/yield data to a dry basis. Feedstock availability and delivered cost data is summarised in Table 1. All costs and profits are expressed in New Zealand Dollars (NZD). Chip and sawdust are produced at primary processing sites, such as saw mills, and typically there is a large surplus of these residues. Pulp logs are the top part of a tree and is unsuitable for structural wood products and are of much lower value than the structural logs. Landings are the large pieces of wood left at landing sites (also known as skid sites) in the forest. Landing sites are locations within the forest where whole logs are cut down further and loaded for transport. Cutover are the braches, limbs and bark that are left on the forest floor where the logging is carried out.
A total of twenty different products were considered based on four main production platforms or routes: sugars, pyrolysis, gasification, and energy and other. Kraft pulp production and energy products were also considered as viable options for residues. The products are categorised in Table 2.

Table 1: Summary of wood processing residue feedstocks, availability and cost

Feedstock/Residues	Feedstock Availability [a] [t/y]	Delivered Cost [$/t]
Pulp Logs	1,000,000	95
Wood Chip	500,000	104
Cutover Residue	185,000	122
Landing Residue	80,000	105
Saw Dust	55,000	78

[a] Biomass on a dry basis

Table 2: Summary of products based on production platform

Sugars Platform	Pyrolysis Platform	Gasification Platform	Energy & Other Products
Ethanol	Pyrolysis Oil	Methanol	Kraft Pulp
Ethylene	Upgraded Pyrolysis Oil	DME	Boiler Fuel
Acetic Acid	Biochar (by-product)	Fischer-Tropsch Liquids	Power
Succinic Acid		Power	Wood Pellets
Levulinic Acid		Ammonia	Compost
Butanol		Urea	

4. Results and discussion

A total of 82 feasible structures were obtained. A feasible structure in P-graph is a processing route or structure that has a total profit greater than zero. The solution with the greatest yearly profit (Feasible structure #1) is shown in Figure 2 and indicates that kraft pulp producing 750,000 t/y of pulp and utilising all available saw dust and landings as boiler fuel is the most economical use of the residues. Total yearly profit was $ 486,100,000, but over 99 % of that coming from kraft pulp. Cutover residues are not included in any of the feasible structures indicating that this resource is not economic under any scenario at the current cost. Only kraft pulp, boiler fuel, wood pellets, pyrolysis oil (with biochar as a by-product), succinic acid, and compost appeared in any of the feasible solutions, meaning these were the only profitable products.

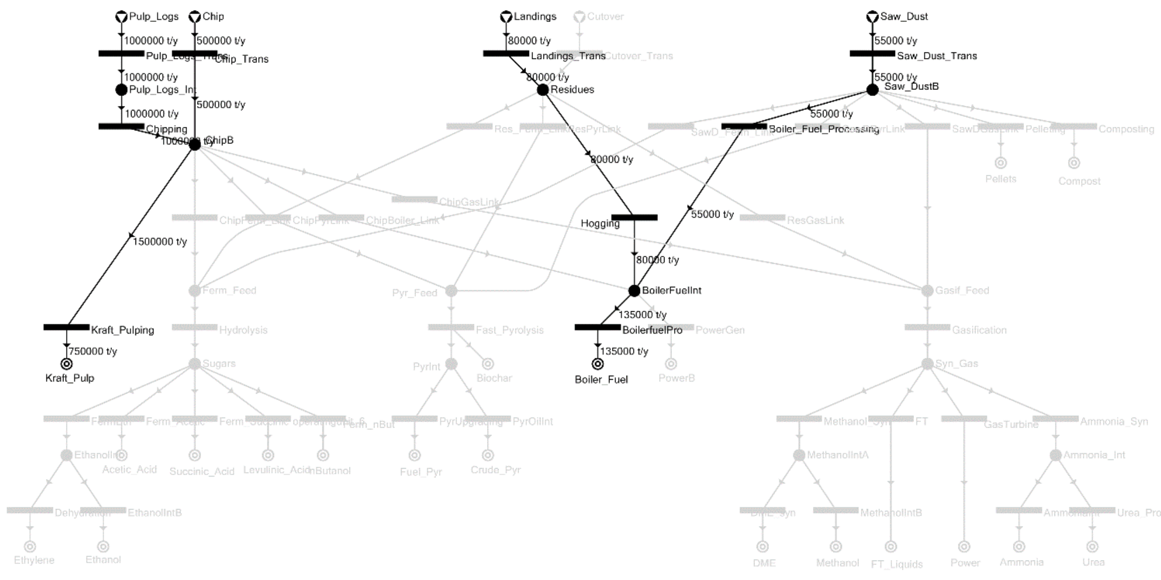

Figure 2: Feasible structure #1 (S1) showing kraft pulp and boiler fuel as the most profitable processing routes

A number of important observations can be made from examining the different feasible solutions and their structures, the order in which they appear, and the reasons for that order. The total annual profit for the top 50 structures is shown in Figure 3 ranked from highest to lowest, and it is clear that there is three distinct regions, which are indicated in the figure. The cause of the regions can be investigated by examining the structures for each region. In each of the three regions all the profitable products were included but the scale and biomass feedstock source for the non-kraft pulp options changed in each structure. The structures that each product appears in is summarised in Table 3.

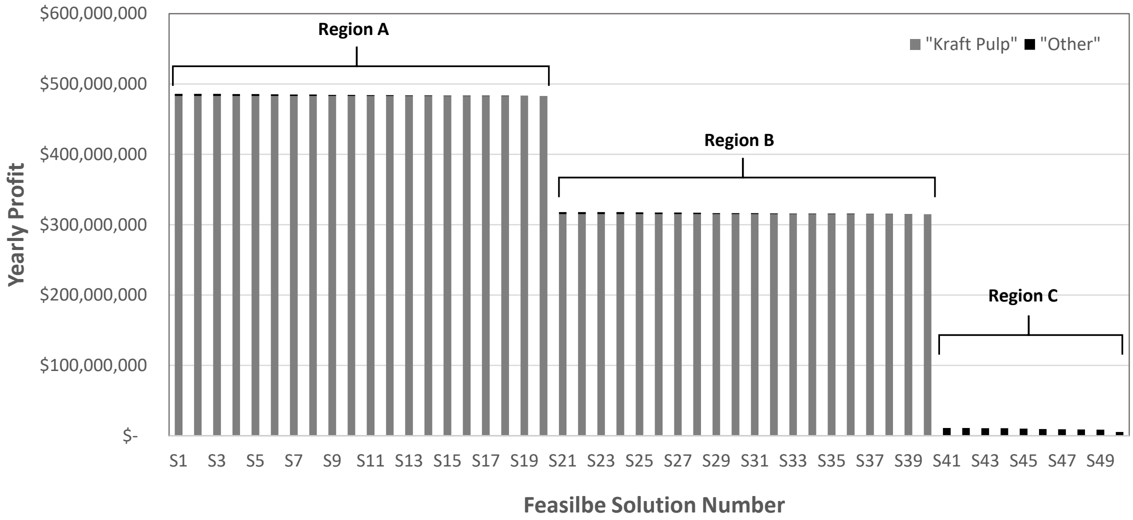

Figure 3: Annual profits for first 50 feasible solutions ranked in order from highest to lowest (right to left)

Table 3: Summary of feasible solutions and the products that appear in each

Product	Feasible Solutions
Kraft Pulp	S1 – S40
Boiler Fuel	S1, S2, S3, S5, S7, S9, S10, S13, S16, S21, S22, S23, S25, S27, S29, S30, S33, S36, S41, S42, S43, S44, S45, S46, S47, S48, S49, S50, S51, S52, S54, S55, S56, S58, S59, S60, S62, S63, S66, S69, S72, S73, S76, S79
Wood Pellets	S2, S4, S8, S22, S24, S28, S42, S51, S53. S60, S65, S70
Pyrolysis Oil (with Biochar)	S3, S4, S5, S6, S11, S12, S14, S18, S23, S24, S25, S26, S31, S32, S34, S38, S43, S44, S51, S52, S53, S54, S55, S56, S57, S58, S61, S62, S63, S64, S65, S66, S67, S68, S71, S74, S75, S77, S81
Succinic Acid	S9, S10, S11, S12, S15, S17, S29, S30, S31, S32, S35, S37, S46, S47, S55, S56, S61, S64, S72, S75, S78, S80
Compost	S9, S11, S13, S14, S15, S19, S29, S31, S33, S34, S35, S39, S46, S48, S55, S58, S61, S68, S72, S74, S76, S77, S78, S82

4.1 Region 1

Region 1 (S1 – S20) included the first twenty solutions and there was only a $3,100,000 difference in profit (less than 1%) between the top rank solution (S1) and the lowest ranked solution (S20). A kraft pulp mill is producing 750,000 t/y generated $ 483,000,000 profit in each solution. All of the pulp log and wood chip was utilised for pulp production and in S20 only the pulp mill was present in the structure. All five other profitable products were also present within this region (except for S20) and with the most profitable to least profitable products being boiler fuel, wood pellets, pyrolysis oil, succinic acid, and compost.

4.2 Region 2

Region 2 (S21 – S40) is exactly the same as region 1 except the kraft pulp mill size has reduced to only 500,000 t/y (the minimum allowable size) with only pulp logs being used. Wood chip was not included in any structure in region 2. The kraft pulp mill generated $ 315,000,000 of profit. The other structures mirrored both order and additional profit above that of the kraft mill to that found in region 1.

4.3 Region 3

In region 3 (S41 – S82) no kraft pulp was produced and only the other five products were included in the feasible solutions. Pulp logs were not an economical feedstock due to the cost of chipping (30 $/t dry). Wood chip was economic for boiler fuel and Pyrolysis oil. As is obvious in Figure 3 there is a huge reduction in annual profits once the kraft pulp mill is no longer feasible.

4.4 Cutover residues

As mentioned cutover was not included in any of the feasible solutions even though there are substantial quantities available. Both the cost of cutover residue and the boiler fuel price were adjusted independently to determine the point where cutover would be included in the feasible solutions (i.e. it became profitable to use). If the cost of cutover residue was decreased from $ 122 to $ 114 per delivered dry ton it became economic to utilise only for boiler fuel. Alternatively when the boiler fuel price was increased by 6.7 % (holding the cutover cost at 78 $/t) all of the cutover was included in the feasible solution. In both instances the amount of boiler fuel produced increased from 135,000 t/y to 320,000 t/y (Figure 4). Small changes in both residue costs and product pricing can cause a large quantity of biomass to be economically viable and vice versa. Improvements in cutover collection methods and technology can reduce costs and prices; while measures such as carbon pricing, can alter the value of the fuel. Increasing the economic use and potential scale of forestry residue as a source of industrial energy will help reduce greenhouse gas emissions by displacing fossil fuels. Understanding the economic trade-offs and scale of the resource is important for both energy users and for public policy makers.

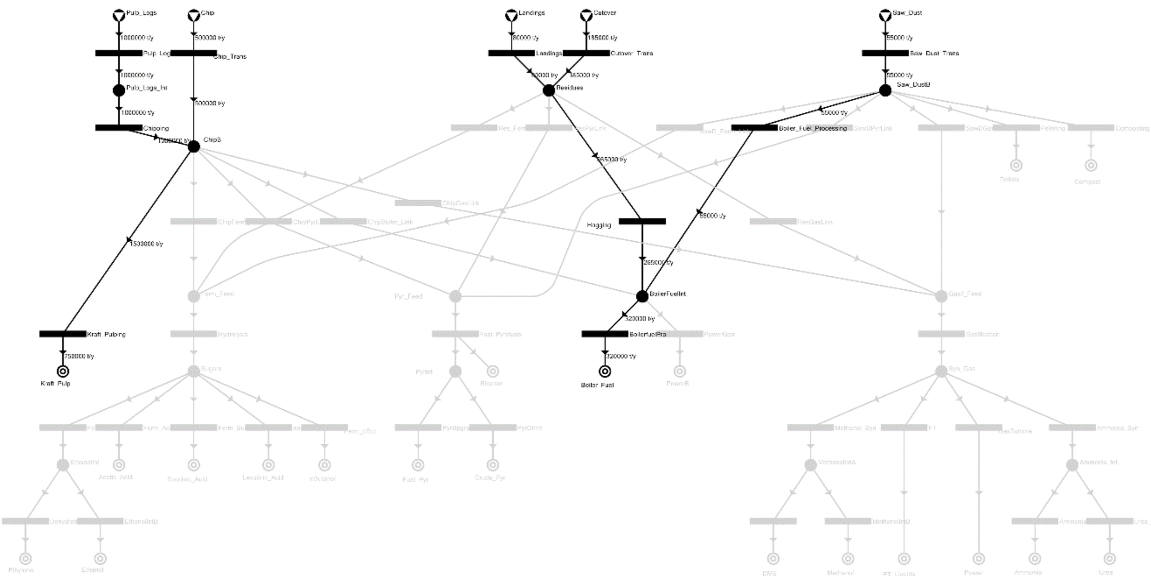

Figure 4: Feasible structure #1b with cutover residues included for boiler fuel

5. P-graph methodology for biomass processing process synthesis

As noted previously there was very little profit differential between solutions in region 1 and all six profitable products were present within this region. Furthermore, when relatively small changes are made to the feedstock cost and/or the product price, additional feedstocks and/or products can become profitable. Feedstock cost has always been the major cost component in most biomass based products. For example, wood cost alone for kraft pulp production can vary from between 25 % to 58 % of the total cost of manufacturing, largely dependent on location and relative cost of other factors such as energy (Pineault, 2006).

A major short coming when examining biomass processing is that only linear cost functions can be used within the P-graph framework. Delivered biomass feedstock costs are often highly non-linear due to biomass source quantity and distance from the mill. Biomass cost and product prices can also be highly variable due to market factors such as supply and demand, and foreign currency exchange rates. This is especially pertinent for commodity products where there is a global market. When emerging products and processes are included in the synthesis problem high levels of uncertainty with respect to product demand, pricing, and both capital and operating costs need to be recognised. The sensitivity of these values and their effect on the final solutions (and their order) mean that some degree of sensitivity analysis or better yet a risk based assessment of the options needs to be developed within the P-graph framework and stress test the various feasible structures.

Succinic acid, for example, is a promising bio-based platform chemical that could be an important green commodity product in the future; however high levels of uncertainty surround the operational and capital costs, and final selling price (Cok et al., 2014). Even though it appears to be feasible in all of the feasible solutions, a -5 % change in the product price removes it completely from the feasible solutions whereas a +5 % makes it the most profitable solution (included with kraft pulp). Such sensitivity is hardly a good basis to make sound decisions on. Likewise if the product price of Levulinic acid is increased slightly it is also included in the feasible solutions. A more robust method than simply a sensitivity analysis is therefore required when emerging products are considered.

5.1 P-graph and Total Site integration of new processes for biorefineries

There can be heat integration benefits when locating new processes with a kraft pulp mill although the benefits depend on the pinch temperature of the two processes (Atkins et al., 2016). Integration of other natural resources and infrastructure, such as renewable electricity, can introduce another dimension to the process selection problem. The economics of the production and capital cost can be affected by the levels of integration between the processes, especially considering the preferred feasible structure may be highly sensitive to small changes in cost. Incorporating an approximate economic benefit (opex and capex) for estimated heat integration between the kraft mill and the gasification platforms into the P-graph problem made no change to the order and the feasibility of these structures. This indicates that based on the current estimated capital and operation cost and product price this platform remains uneconomical at this scale even with Total Site integration. Further work is required to determine at what scale these routes might become economical and how integration might assist.

5.2 Future Work

The simplicity and merits of the P-graph framework justify further development of both the approach and the tools to facilitate incorporation of non-linear cost functions. If one of the objectives and outcome of P-graph is to identify the economically optimal process synthesis route, then these shortcomings need to be addressed, otherwise the impact of P-graph, especially to the economic utilisation of biomass, will be limited. To address uncertainty in process synthesis stochastic programming methods have been used (Sahinidis, 2004). Future work will look at how stochastic programming methods can be integrated into the P-graph framework whilst preserving the unique P-graph approach and user-friendly aspects of the method.

6. Conclusions

P-graph has been used to determine the profitability of utilising wood processing residues and identified kraft pulp production and boiler fuel as the most profitable. Products included in the feasible solutions and the source of residues are all finely balanced, and slight changes in feedstock cost, product price, and operational and capital costs can cause major changes to the makeup and order of feasible structures. Potential heat integration between the kraft mill and the gasification routes did not yield enough benefit to make them economically feasible. The P-graph approach has some limitations when considering biomass and these will be addressed in future work.

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