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Biomass Supply and Inventory Management for Energy Conversion

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Seasonal availability of supply and demand market of biomass is one of the challenges for its energy conversion. A suitable production planning approach is required to consider the dynamic characteristic. This study aims to identify the production rate, inventory and supply flow of biomass by integrating Pinch Analysis and mathematical model. Storage to overcome the deficits of biomass supply at the following time interval is also identified. The demonstrated case study suggested a fix production rate of 22,000 GJ/month and adapted to 6,167 GJ/month after the pinch point to meet the fluctuating demand. The required inventory is also suggested. For example, 3,167 GJ of product (bio-oil) inventory on Month 4 to meet the following demand, and with 3,764.1 GJ (301 t) of biomass as storage to overcome the supply deficit (fluctuated) in the following month. The mathematical approach optimises the biomass network flow (allocation) at each time intervals (Month). Emission and transporting cost, as well as the energy content of the biomass resources, are considered. Pinch Analysis serves as an effective tool in providing a starting solution dealing with fluctuating supply and demand for further planning.

1. Introduction

Biomass to energy conversion receives increasing attention due to the concerns on energy security and GHG emissions from fossil fuel consumption. The sources of biomass are the forest, edible crops, dedicated biomass, residues and waste. The main challenge of the biomass supply chain is the source which is disseminated over a large area and influenced by a strong seasonality (Lautala et al., 2015). Acuna et al. (2019) divide the biomass supply chain decisions into strategic, tactical and operational levels. The efficiency of supply chain management is crucial for the economic and environmental viability of the conversion plant. Mathematics optimisation has been essential in facilitating the decision making of this complex management. The other methods are a simulation, geographic information system, and heuristics. Mixed-integer linear programming and multi-criteria decision analysis among the most applied method. How et al. (2016) integrates P-graph framework and mathematical modelling to identify the optimal number and location of hubs as well as the allocation design. Akgul et al. (2014) applied Mixed-integer nonlinear programming to determine the optimal design of a bioelectricity supply chain in the UK by optimising the cost and emission. Shabani et al. (2016) consider the uncertainties in biomass quality by stochastic programming. Lim et al. (2019) tackle the insecure supply of biomass by using element targeting approach and multiperiod analysis. Zandi et al. (2018) highlighted that the studies integrate decisions such as plant localisation and dimensioning in biomass supply design is scarce. Pinch Analysis (Linnhoff et al., 1982) is one of the potential methods. It is originally for heat integration problem and has been extended widely in recent years (Klemeš et al., 2018). This targeting approach with graphical representation is suitable for practical purpose, easier to understand by the practitioner and serve as an excellent platform in minimising the problem size for the following detail planning. Lam et al. (2011) apply the Pinch concept and clustering approach for regional resource management. Production Pinch Analysis is among the graphical heuristic method, which could be used for biomass supply chain planning. It has been proposed by Singhvi and Shenoy (2002) in general for supply chain planning, to identify the production rate for a given demand forecast. A total of 6 Pinch production strategies have been later summarised by Ludwig et al. (2009). However, the proposed approach has not been well demonstrated

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through biomass supply chains case study. The main discussion is focused on interpreting the possible strategies. This study aims to integrate Pinch Analysis for targeting and mathematical model for the follow-up optimisation of the production rate, product inventory (e.g. bio-oil), biomass storage and biomass network flow (allocation). The biomass to energy demand is satisfied in a way that maximises the profit through minimising the inventory. The biomass network flow is optimised by reducing the cost incurred in transporting and carbon tax (environmental price).

2. Method

2.1 Pinch Analysis

Pinch Analysis for aggregated planning by Singhvi and Shenoy (2002) is adapted to estimate the possible production rate and inventory level of biomass to energy conversion. Y-axis is replaced with energy to fit the purpose of the case study. The profit is maximised by minimising the inventory (product accumulation). Insufficient inventory to fulfil the demand leads to a loss in sales and profits while a surplus of inventory results in unnecessary costs. Figure 1a shows the composite curves example and its interpretation. The Composite Curves are Demand Curve and Production Curve. Demand Curve is plotted by cumulative demand at different time. Production Curve is identified by rotating the horizontal axis from the starting inventory as the pivot until it touches the Demand Curve as described by Singhvi and Shenoy (2002). Grand Composite Curve is plotted by minus the Production Curve by Demand Curve. It is a graphical representation that useful in showing the distribution of product inventory (e.g. bio-oil accumulates) at various time. The supply of biomass is subjected to seasonality and availability. Biomass storage is needed to fulfil the demand and production rate at each time interval. It can be determined by further extending the Pinch Analysis (see Figure 1b), where a grand composite curve is plotted by minus Supply Availability Curve by Production Curve for excessive availability of supply. The required supply (and hence the biomass storage for low supply period) at a various time can be identified for further biomass flow (from which source and its amount) optimisation.

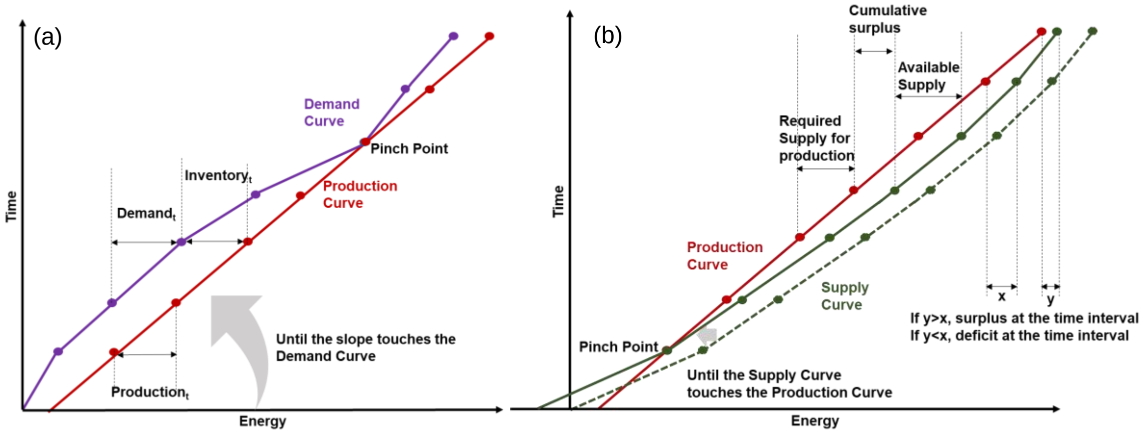


Figure 1: Composite Curves of aggregate planning in supply chain (a) Demand (Purple) and Production (Red) Curve; (b) Production (Red) and Supply (Green) Curve

2.2 Optimisation model

The biomass flow (sources - location and amount) is identified by Eq(1) and Eq(2) with the consideration of energy content (GJ/ t) of biomass, transporting distance, load (required supply) and the number of trip. The identified required supply at various time by Pinch Analysis has to be fulfilled. The objective function is minimising the cost, includes both transportation and GHG emission.

$$Min_{cost} = \sum_k (n \cdot e_{empty} + L \cdot e_{load}) D_k \times GHG_{cost} + (L_k \times D_k \times T_{cost}) \tag{1}$$

$$n = Roundup\left(\frac{L}{W_{max}}\right) \; and \; n \in Z^+ \tag{2}$$

Where e_{empty} is the specific emission of an empty transport vehicle fleet (g/km); e_{load} is the marginal specific emission of a transport vehicle fleet per t of transport load (g/tkm); n is the required number of transport vehicles; D is the transport distance that each vehicle has to travel (km), and L is the total transport load across all vehicles (t). GHG_{cost} is the GHG pricing (e.g. carbon tax), T_{cost} is the transporting cost; k is the source of biomass, in this study labelled as S1-S6. $W_{max}$is the maximum capacity of the transport mode. Eq(1) is accompanied by two constraints listed in Eq(3) and Eq(4). The total supply amount $(S_{k)})$ multiply by energy content per t of biomass (EC_k) and energy conversion efficiency (CE) has to equal to the identified required supply (IRS) at each time intervals. The amount of supply at each source point (S_k) cannot exceed its available supply.

$$IRS = \sum_k (S_k \times EC_k \times CE) \quad (3)$$

$$S_k \leq Available\ supply \quad (4)$$

3. Case study

The method is demonstrated through a case study where 6 locations with different type and amount of biomass are illustrated, as in Table 1 and Figure 2. The energy demand (bio-oil) in 6 different months is listed in Table 2. Table 3 shows the other information for targeting and optimisation. The energy conversion of this study is assumed as 60 %, and the transporting mode is lorry with the specification as in Table 3.

Table 1: Source of biomass

Source Location	Energy Content (GJ/t)	Available Biomass Supply (t)					
		Month 1	Month 2	Month 3	Month 4	Month 5	Month 6
S1	17.17	0	300	0	0	300	0
S2	18.58	2,000	1,800	0	0	100	0
S3	19.3	100	0	0	0	300	0
S4	14.83	0	300	0	100	0	100
S5	20.81	0	0	700	500	0	0
S6	20.81	300	0	800	500	0	0

Table 2: Energy demand at each time interval

Month	Energy Demand (GJ)
1	20,000
2	7,000
3	40,000
4	3,000
5	5,000
6	10,000

Table 3: Input data

Other Information	Assumptions/ Value	Reference
Pyrolysis	60 % conversion efficiency	
GHG Price	56.6 €/t	CE Delft (2017)
Transporting Cost	0.16 €/tkm	IEA (2019)
Transportation mode (Lorry)	Emission factor = 76 g/tkm	Boer et al. (2016)
	Weight of empty lorry (Bodyweight) = 60 t	Boer et al. (2016)
	Maximum capacity = 40.8 t	Boer et al. (2016)
	e_{empty} = 1,845.71 g/km; e_{load} = 30.76 g/tkm	Fan et al. (2019)

The location of treatment plant (pyrolysis) is proposed by using the centre of gravity method, as reviewed by Onnela (2015), considering the distance and biomass availability, see Eq(5) and Eq(6). The Euclidean distance, which is rotational invariance, can be identified by Eq(7). The route distance can be applied if the data is available (e.g. by Geographic Information System) The biomass flow (in each location and months) is optimised using Eq(1) after targeting by Pinch Analysis.

$$x_t = \sum_k x_k.A_k \div \sum_k A_k \quad (5)$$

$$y_t = \sum_k y_k . A_k \div \sum_k A_k \tag{6}$$

$$D = \sqrt{(x_k - x_t)^2 + (y_k - y_t)^2} \tag{7}$$

x_t is the x coordinate of the optimal treatment plant location; y_t is the y coordinate of the optimal treatment plant location; x_k is the x coordinate of the biomass source, y_k is the y coordinate of the biomass source; A_k is the available supply.

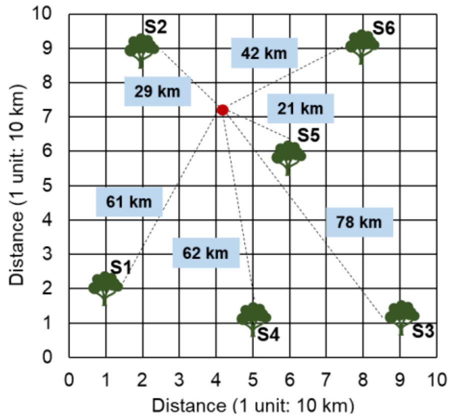


Figure 2: Location and distance of the assessed case study. The red dot represents the treatment plant location

4. Results and discussion

Figure 3 shows the identified production rate and inventory by Pinch Analysis. The fixed production rate is identified as 22,000 GJ/month. It can be decreased (adapted) to 6,167 GJ/month after the Pinch Point to minimise the bio-oil inventory. The workforce and number of hired are reduced accordingly. Another option of production rate after Pinch Point is 9,067 GJ/month (with the surplus product/utility), where all the available biomass supply would be processed (Figure 4) if there is possible additional demand (e.g. non bio-oil to energy purpose).

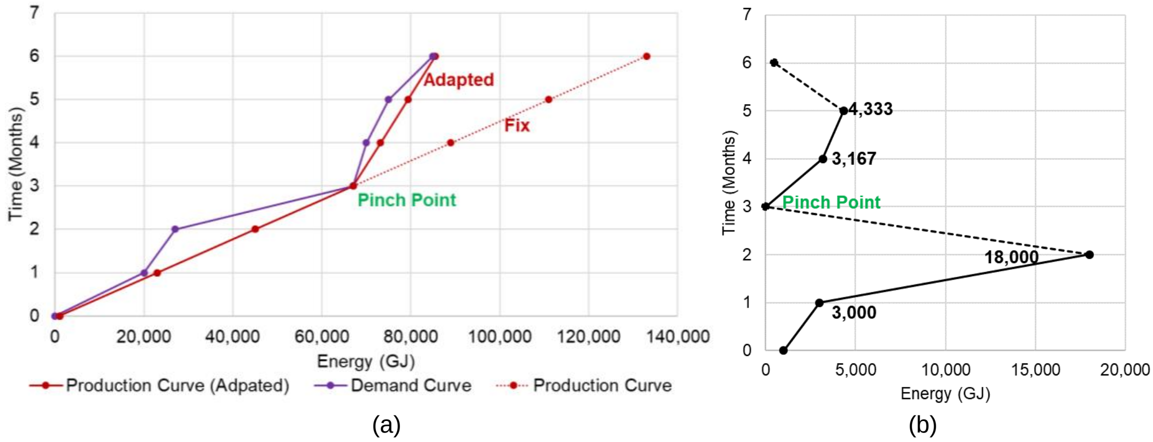


Figure 3: (a) Composite Curves of demand and production rate and (b) the Grand Composite Curve showing product (bio-oil) inventory

By referring to the Supply Availability Curve (Figure 4), the biomass supply is generally higher than the production rate. However, there is a surplus or deficit at each time interval, as shown in the Grand Composite Curve in Figure 5. Biomass storage is required to overcome the deficit on Month 3 and 6. The identified values are 3,271.4 GJ (302 t) on Month 2, 3,764.1 GJ (301 t) on Month 4 and 1,512.8 GJ (138 t) on Month 5. Different network flow and source can be chosen to obtain the required biomass supply for energy conversion.

Eq(1) is applied to obtain the flow with the lowest emission and transporting cost, as illustrated in Figure 6. For example: 3 biomass sources (S4 = 100 t, S5 = 500 t, S6 = 500 t) are available in Month 4; the selected sources are S5 = 500 t, S6 = 295 t (Figure 6) with the optimised cost of 3,581 € (0.36 €/t, Month 4). The average cost for 6 months is 0.51 €/t (43,253 €).

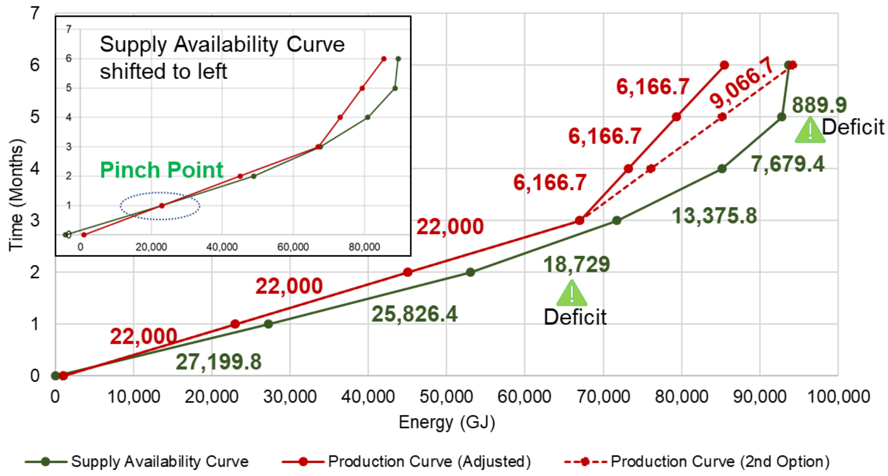
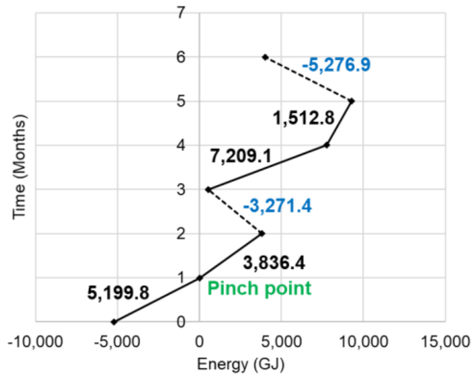


Figure 4: Composite Curves of production and available supply.



Month	Available Supply (GJ)	Required Supply (GJ) based on Production Curve	Storage (GJ)
1	27,199.8	23,000.0	0
2	25,826.4	23,000.0	3,271.4
3	18,729.0	23,000.0	Deficit
4	13,375.8	6,166.7	3,764.1
5	7,679.4	6,166.7	1,512.8
6	889.9	6,166.7	Deficit
Storage required to overcome the deficit on Month 3 and 6			

Figure 5: The Grand Composite Curve showing excessive and deficit biomass availability as well as the identified required supply. Value in blue font (at negative gradient) indicates the deficit at that time interval.

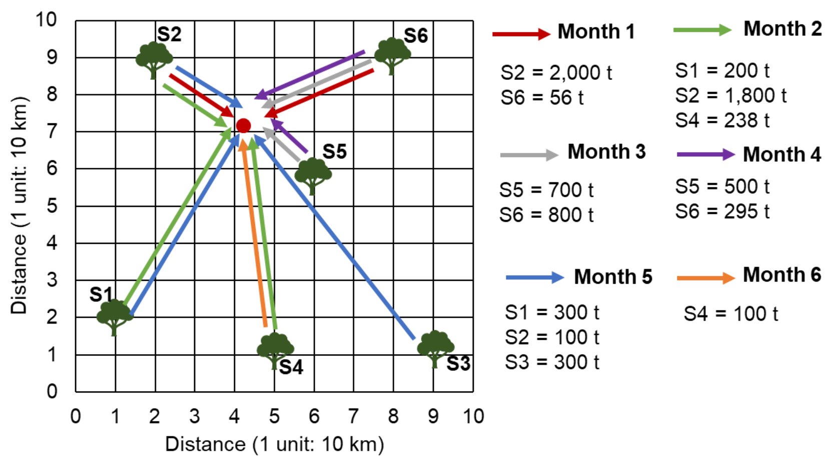


Figure 6: The biomass flow in each time intervals (Month) to fulfil the demand, considering the required inventory and storage

5. Conclusions

The applicability of Pinch Analysis in production, inventory and storage planning has been demonstrated. This simple heuristic method is relatively easier to understand for production planning with seasonal supply and demand. Results of the case study suggest a production rate of 22,000 GJ/month (Month 1 - 3) and 6,167 GJ/month (Month 4 - 6). To fulfil a total energy demand of 85,000 GJ, which does not distribute evenly across the month, inventory (Month 1 = 3,000 GJ; Month 2 = 18,000 GJ; Month 4 = 3,167 GJ; Month 5 = 4,333 GJ) is needed. Biomass storage of 302 t on Month 2, 301 t on Month 4 and 138 t on Month 5 are required to overcome the deficit on Month 3 and 6. The biomass flow (sourcing/allocation) is optimised for the lowest emission and transporting cost solution (0.51 €/t). Pinch Analysis can be even further extended as it offers the room for the inclusion of social preferences to the planning. An optimum target is identified for the following analysis with the mathematical model. However, the case study used a simplified picture of biomass supply chain to demonstrate the methodology. Uncertainty of supply, degradation during the holding time, pre-treatment, inclusion of a wider range of transportation mode, the transfer station and scheduling are going to be developed in future study.

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