Sustainable Supply Network Design through Optimisation with Clustering Technique Integration

Wendy P. Q. Ng, Hon Loong Lam*

Centre of Excellence for Green Technologies, The University of Nottingham, Malaysia Campus, Broga Road 43500
Semenyih, Selangor D. E., Malaysia
HonLoong.Lam@nottingham.edu.my

Network complexity between elements in large data sets reduces the group's feasibility for single element analysis in regards to time and cost. Clustering of elements into several minor groups allows the display of clearer group's development and introduction of simpler yet centralised industrial management. The clustering of engineering facilities, particularly, allows the analysis of industrial business development and network links among the engineering facilities in the cluster.

In this work, a demonstrating case study on biomass utilisation is developed for optimised supply network design. The facilities are grouped into clusters for industrial management based on their material interactions. The material supply and process network is optimised economically and its environmental emission is taken into consideration. The processing facilities are interacted through industrial symbiosis approach. The flexibility of the model is improved with the model's capacity to allocate external interruption (e.g., potential investments). This work incorporates the economic, environmental and social aspects in the industrial supply network design.

1. Introduction

The network links among groups in large amount of data increase the network's complexity, which results in the infeasibility of single point analysis in regards to time and cost. Various physical clustering techniques have been well developed previously (Wanner, 2004). Recently, clustering techniques are integrated with optimisation system for optimal process and network design. Lam et al. (2011) developed model-size reduction techniques for the analysis of large-scale renewable production and supply networks; whilst, Ng et al. (2012) presented a novel method for process heat exchanger network integration and decomposition via clustering approach. These integrated techniques improved the optimisation solution time, induced cost saving and reduction in network complexity. The clustering and optimisation techniques can be extended for the application on supply network design.

The first application of optimisation on supply chain by pinch analysis was carried out by Singhvi and Shenoy (2002). They presented a novel extension of the targeting methods from pinch analysis to aggregate planning in supply chains. Later, Foo et al. (2008) extended the scope with supply network cascade analysis. Lam et al. (2010) continued the work by extending the scope to biomass supply network synthesis.

Maximum economic performance of a supply network model has always been the key parameter for supply network optimisation. However, it should be noted that supply network can be designed based on compromising economic and environmental impact. Sustainable supply network design is being emphasised in the current global development (Young et al., 2012). The carbon emission along the supply network can be investigated and the environmental impact factor can be integrated into the supply network design for the generation of a green supply chain system. Furthermore, supply network design may be extended to engage the industrial symbiosis approach which maximise resource utilisation. In this work, a supply network is generated based on compromising economic, environment and social sustainability factors with the integration of industrial symbiosis approach. The facilities in the network are further

grouped into clusters for industrial cluster formation. The concept of industrial cluster formation is illustrated in Figure 1.
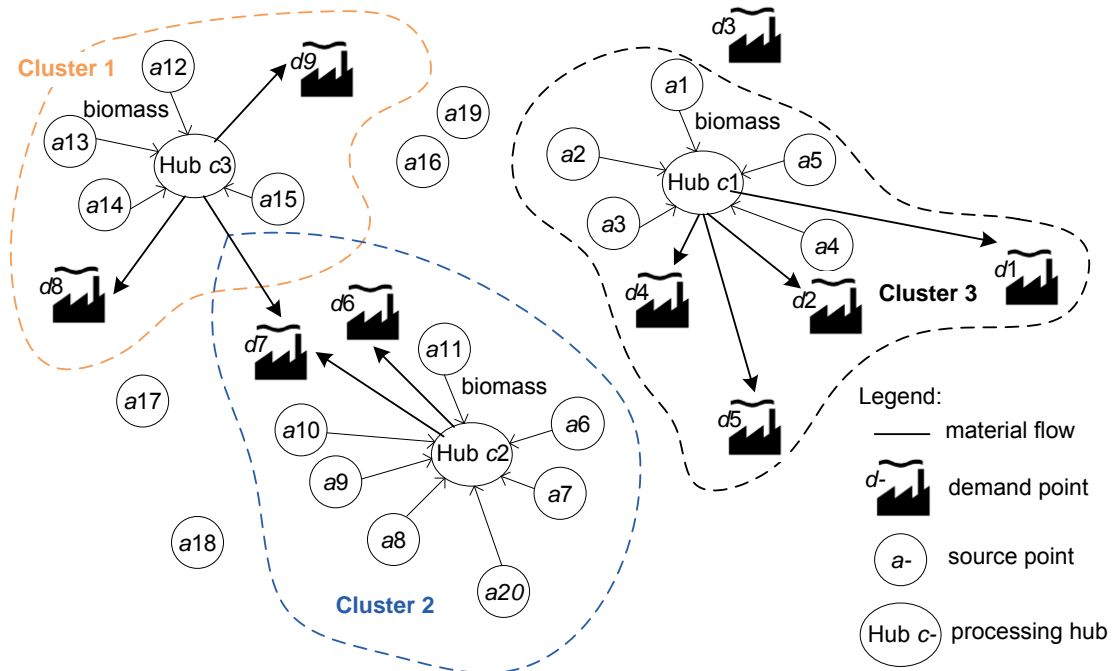

Figure 1: The concept of industrial cluster formation

2. Problem statement

The problem to be addressed in this work is formally stated as follows: a set of biomass from source $a \in A$ with biomass type $b \in B$ is to be allocated to a set of centralised processing site/hub $c \in C$. In hub c, biomass b is converted to product e. The biomass product(s) $e \in E$ is/are sent to a set of demand point $d \in D$. Clusters are formed, which every cluster consists of one processing hub c, its interacted biomass sources and demands sets.

The transportation cost of the model is estimated based on the amount of material transferred across its sources, processing facilities and demand points. The economic performance of the model is simplified as gross profit which takes into consideration of product's revenue, unit operation's operating cost and capital cost as well as raw material cost. The model is optimised to achieve maximum economic potential as highest profit, minimum logistic emission as minimum environmental impact and maximum waste utilisation as social's sustainability for maximum material recovery. These objective functions are optimized simultaneously using fuzzy programming (Zimmermann, 1978).

3. Model formulation

Biomass flow ($F^I_{a,b,c}$) from source points a of component b to processing site c is constrained or upper-bounded by its availability.

$$\sum_c F^I_{a,b,c} \leq X_b \times CAP_a \qquad \qquad \forall\, a \in A,\, b \in B \qquad (1)$$

where X_b is biomass produced per unit of raw material processed (%wt.); CAP_a is the raw material availability (t/h).

Biomass sent to processing site / hub c is further processed into intermediate and final value-added products:

$$F^{II}_{b,c,e} = \sum_a F^I_{a,b,c} \qquad \qquad \forall\, b \in B,\, c \in C,\, e \in E \qquad (2)$$

$$F^{III}_{c,e} = Y^I_{b,e} \times \sum_a F^{II}_{b,c,e} \qquad \qquad \forall\, b \in B,\, c \in C,\, e \in E \qquad (3)$$

$$F_{c,e}^{IV} = Y_e^{II} \times F_{c,e}^{III} \qquad\qquad \forall\, c \in C, e \in E \qquad (4)$$

where $F_{b,c,e}^{II}$ is the conversion of biomass b into intermediate product e in processing hub c (t/h); $Y_{b,e}^{I}$ and Y_e^{II} are biomass conversion factors (%wt.) to intermediates and final products respectively; $F_{c,e}^{III}$ and $F_{c,e}^{IV}$ are intermediates and final products flowrates (t/h).

Products produced are delivered to demand points d to fulfill the minimum demand requirements:

$$\sum_d F_{c,d,e}^{V} = F_{c,e}^{IV} \times B_{c,e}^{I} \qquad\qquad \forall\, c \in C, e \in E \qquad (5)$$

$$DEM_{d,e} \leq \sum_c F_{c,d,e}^{V} \times B_{c,d,e}^{II} \qquad\qquad \forall\, d \in D, e \in E \qquad (6)$$

where $F_{c,d,e}^{V}$ is product e flowrate (t/h) delivered from processing hub c to demand point d; $B_{c,e}^{I}$ is binary variable denotes the existence of processing pathway of e in hub c; $B_{c,d,e}^{II}$ is binary variable denotes the existence of delivery pathway of product e from c to d; $DEM_{d,e}$ is minimum product e demand at sink d (t/h).

The product supply is constrained that each demand point can have only one supplier for each type of product:

$$\sum_c B_{c,d,e}^{II} \leq 1 \qquad\qquad \forall\, d \in D, e \in E \qquad (7)$$

Each processing hub is designed to fulfill a positive rate of return (*ROI*) for its operational lifespan over 20 years with operation hour of 6,000 h/y:

$$\sum_d F_{c,d,e}^{V} \times PRI_e \times 20 \times 6{,}000 \geq C_e^{TCAP} \times B_{c,e}^{I} \times ROI \qquad \forall\, c \in C, e \in E \qquad (8)$$

where PRI_e is product selling price (USD/t); C_e^{TCAP} is unit operation capital cost (USD).

The material is transported by means of heavy duty truck using 100 % diesel oil as fuel. Its incurred cost is estimated using simplified cost function:

$$TC = \sum_{a,b,c} C^{TR} \times DT_{a,c} \times F_{a,b,c}^{I} + \sum_{c,d,e} C^{TR} \times DT_{c,d} \times F_{c,d,e}^{V} \qquad (9)$$

where *TC* is transportation cost (USD/h) for biomass and product delivery; C^{TR} is transportation cost (0.10 USD/t-km); $DT_{a,c}$ and $DT_{c,d}$ are delivery distance (km) from source a to hub c and hub c to sink d respectively.

The gross profit (*GP*) gained from each hub is estimated:

$$GP = \sum_{a,b,c,d,e} F_{c,d,e}^{V} \times PRI_e - F_{c,e}^{IV} \times C_e^{OPE} - F_{c,e}^{IV} \times C_e^{CAP} - F_{a,b,c}^{I} \times C_b^{RAW} \qquad (10)$$

$$GP \geq TC \qquad (11)$$

where C_e^{OPE} and C_e^{CAP} are operating cost and capital cost (USD/t) for product e unit operation; C_b^{RAW} is raw material cost (USD/t).

The energy balance for utilities consumption in each hub is defined:

$$MPS_c = F_{c,MPS}^{IV} - \sum_e \left(F_{c,e}^{IV} \times Z_e^{MPS} \right) \qquad\qquad \forall\, c \in C \qquad (12)$$

$$ELE_c = F_{c,ELE}^{IV} - \sum_e \left(F_{c,e}^{IV} \times Z_e^{ELE} \right) \qquad\qquad \forall\, c \in C \qquad (13)$$

$$MPS_c \geq 0 \qquad\qquad \forall\, c \in C \qquad (14)$$

$$ELE_c \geq 0 \qquad\qquad \forall\, c \in C \qquad (15)$$

where MPS_c and ELE_c are medium pressure steam consumption (t/h) and electricity consumption (kWe/h) respectively; Z_e^{MPS} and Z_e^{ELE} are medium pressure steam and electricity consumption factors per unit of product e produced.

The environmental emission volume (*EMS*) due to material delivery is estimated:

$$EMS = E \times \left(\sum_{a,b,c} F_{a,b,c}^{I} \times DT_{a,c} + \sum_{c,d,e} F_{c,d,e}^{V} \times DT_{c,d} \right) \qquad (16)$$

where E is heavy duty diesel truck emission factor (0.06 kg CO_{2e}/t-km).

This multiple objectives supply network design is optimised based on the criteria: i) maximum economic performance through optimal technologies selection; ii) maximum biomass (waste) utilisation for maximum material recovery; iii) minimum transportation cost incurred for material delivery; iv) minimum environmental impact through minimal logistic emissions. This multiple objectives optimisation is carried

out by applying fuzzy optimisation theory. The respective interdependent fuzzy variable which forms the limiting parameter for objectives satisfaction is formulated:

$$\frac{(GP - TC) - (GP - TC)^{LB}}{(GP - TC)^{UB} - (GP - TC)^{LB}} \geq \lambda \tag{17}$$

$$\frac{\sum_{c,d,e}(F_{c,d,e}^{V} - F_{c,d,e}^{VLB})}{\sum_{c,d,e}(F_{c,d,e}^{VUB} - F_{c,d,e}^{VLB})} \geq \lambda \tag{18}$$

$$\frac{EMS^{UB} - EMS}{EMS^{UB} - EMS^{LB}} \geq \lambda \tag{19}$$

where λ is the degree of satisfaction / fuzzy variable; the indexes UB and LB stand for the upper bound and lower bound of the variables that it can reach if the variables serve as objective functions.
The objective of the model is to maximize the contribution of each objective or degree of satisfaction:

$$OBJ = MAX \ \lambda \tag{20}$$

4. Illustration cast study

A palm biomass case study is demonstrated to illustrate the application of the propose technique. Palm biomass is collected from 55 palm oil mills (POMs). 20 POMs with the highest biomass availability are selected as possible processing hub. Biomass is delivered to these possible processing hubs and converted to value-added products in hub. These products are then delivered to 16 demand points to fulfil their minimum product requirements. The shortest great-circle distances among sources, sinks and processing hubs are used for transportation consideration and cost calculation. The sets information for model development is listed in Table 1.

Table 1: Sets defined in case study for model development

Sets	Values
Number of biomass sources a	55
Type of raw materials b	2
Number of possible processing hubs c	20
Number of demand points d	16
Type of products e	6

A mixed-integer non-linear programming (MINLP) model is formulated and optimised using the modelling software General Algebraic Modelling System (GAMS) 23.4.3 (GAMS, 2013). The model parameters used in the model and the optimisation results are shown in Table 2. Each processing hub is assumed to achieve a rate of return of one-third of its allocated investment per year over its 20 y lifespan or a 3 y payback period. The utilities, i.e. steam and electricity, consumption in each processing hub is constrained to be self-sustaining that part of the biomass is used to generated utilities to support its unit operations. However, any excess utility generated can be exported to external facilities.

Table 2: Parameters and results for case study

Parameter / Result	Unit	Value
Fuzzy optimisation boundaries		
Upper bound for economic potential, $(GP - TC)^{UB}$	USD/h	16,432
Lower bound for economic potential, $(GP - TC)^{LB}$	USD/h	0
Upper bound for biomass utilisation, $\sum_{c,d,e} F_{c,d,e}^{VUB}$	t/h	7,859
Lower bound for biomass utilisation, $\sum_{c,d,e} F_{c,d,e}^{VLB}$	t/h	318
Upper bound for environmental impact, EMS^{UB}	kg CO_{2e}/t-km	2,599,733
Lower bound for environmental impact, EMS^{LB}	kg CO_{2e}/t-km	3,175
Gross profit, GP	USD/h	22,728
Transportation cost, TC	USD/h	17,299
Environmental emission, EMS	kg CO_{2e}/t-km	10,379
Fuzzy variable, λ		0.33

The model makes an overall profit (profit after logistic cost) of 6.52×10^8 USD/y. Out of 20 possible processing hubs, 11 are chosen for operation.

In the model, cluster is defined to consist of one processing hub and its interacted sources and sinks. The clusters formed and their associated facilities, supply sources and demand sinks are listed in Table 3.

Table 3: Cluster formation and their associated material sources and consumers (sinks)

Cluster	Processing hub *c*	Source *a*	Sink *d*
1	1	1, 2, 3, 5, 29, 35, 38	6, 11
2	4	7, 8, 9, 10, 11, 13, 33	1, 6, 7
3	5	14, 15, 16	4, 9
4	7	4, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 36, 40	4, 8, 9, 10, 15
5	10	25	
6	12	30, 31, 32, 33, 34, 35, 36, 38, 39, 40, 41, 42	12, 13
7	13	34	8
8	16	6, 7, 37, 45	14
9	17	43, 44, 46, 47, 48, 49, 50, 51, 53, 54, 55	1, 2, 3, 5
10	19	37, 46, 52	16
11	20	54	2

5. Error analysis of model

Assumptions were made in evaluating the model practicability:
   a) Minimum product requirement of demand points was set, yet open and readily available market for products was assumed.
   b) The model assumed for no leakage emission and material loss from logistic activity.

These assumptions reduced the supply network's realism, however, the main objective of this work is to introduce another discipline of clustering technique for industrial management and supply network optimisation.

6. Conclusions

This work presented an industrial clustering of facilities according to its material interaction. Each cluster is constrained to consist of one processing hub which forms the seed of the cluster. In the case study, 11 out of 20 possible processing hubs are selected and these hubs form the cores of 11 industrial clusters. This clustering of facilities significant the industrial interaction in groups and induces possibly industrial symbiotic practices among facilities in each cluster.

The model can be further developed to evaluate future investment allocations. This enables the modelling of industrial cases and acts as a tool of decision making for the allocation of new industrial facilities. Furthermore, the model can be extended to include other industrial facilities, which industrial symbiotic practise – the supply of excess resources to needy facilities for maximum material recovery and utilisation. On the other hand, the supply network model can be further developed for optimisation.

Nomenclatures

a	set of biomass sources (palm oil mills)
b	set of raw materials (palm biomass)
c	set of processing hubs
d	set of demand points (factories/consumers)
e	set of value-added products
$F_{a,b,c}^{I}$	biomass flowrate from source points *a* of component *b* to processing hub *c* (t/h)
$F_{b,c,e}^{II}$	flowrate of biomass b processed into intermediate *e* in processing hub *c* (t/h)
X_b	biomass produced per unit of raw material processed (% wt.)
CAP_a	raw material availability (t/h)

$Y_{b,e}^{I}$	biomass conversion factors to intermediates (% wt.)
Y_{e}^{II}	biomass conversion factors to final products (% wt.)
$F_{c,e}^{III}$	intermediates products flowrates (t/h)
$F_{c,e}^{IV}$	final products flowrates (t/h)
$F_{c,d,e}^{V}$	product e flowrate delivered from processing hub c to demand point d (t/h)
$B_{c,e}^{I}$	binary variable denotes the existence of processing pathway of e in hub c (1)
$B_{c,d,e}^{II}$	binary variable denotes the existence of delivery pathway of product e from c to d I2(1)
$DEM_{d,e}$	minimum product e demand at sink d (t/h)
ROI	return on investment
PRI_{e}	product selling price (USD/t)
C_{e}^{TCAP}	total unit operation capital cost (USD)
TC	transportation costs for biomass and product delivery (USD/h)
C^{TR}	transportation cost (USD/t-km)
GP	gross profit (USD/h)
C_{e}^{OPE}	operating cost of product e unit operation (USD /t)
C_{e}^{CAP}	capital cost of product e unit operation (USD /t)
C_{b}^{RAW}	raw material cost (USD /t)
MPS_{c}	medium pressure steam consumption in hub c (t/h)
ELE_{c}	electricity consumption in hub c (kWe/h)
Z_{e}^{MPS}	medium pressure steam consumption factors per unit of product e produced (1)
Z_{e}^{ELE}	electricity consumption factors per unit of product e produced (1)
$DT_{a,c}$	delivery distance from source a to processing hub c (km)
$DT_{c,d}$	delivery distance from processing hub c to demand point d (km)
EMS	environmental emission volume (kg CO_{2e})
E	heavy duty diesel truck emission factor (kg CO_{2e}/t-km)
λ	degree of satisfaction / fuzzy variable (1)
UB	upper bound
LB	lower bound
OBJ	objective function

References

Foo D.C.Y., Ooi M.B.L., Tan R.R., Tan J.S., 2008, A heuristic-based algebraic targeting technique for aggregate planning in supply chains, Comput Chem Eng, 32, 2217-2232.

GAMS, 2013, The GAMS System <www.gams.com/docs/intro.htm> accessed 05.03.2013

Lam H.L., Foo D.C.Y., Kamal M., Klemeš J.J., 2010, Synthesis of regional energy supply chain based on palm oil biomass. Chemical Engineering Transactions, 21, 589-594. doi: 10.3303/CET1021099

Lam H.L., Klemeš J.J., Kravanja Z., 2011, Model-size reduction techniques for large-scale biomass production and supply network. Energy, 36(8), 4599-4608.

Ng W.P.Q., Tokos H., Lam H.L., Yang Y., 2012, Process Heat Exchanger Network Integration and Decomposition via Clustering Approach. Computer Aided Chemical Engineering, 31, 1562-1566.

Singhvi A., Shenoy U.V., 2002, Aggregate Planning in Supply Chains by Pinch Analysis, Trans IChem, 80, Part A, 597-605.

Wanner L., 2004, Introduction to Clustering Techniques <www.iula.upf.edu/materials/040701wan-ner.pdf> accessed 05.05.2012

Young D.M., Hawkins T., Ingwersen W., Lee S.-J., Ruiz-Mercado G., Sengupta D., Smith R.L., 2012, Designing Sustainable Supply Chains, Chemical Engineering Transactions, 29, 253-258.

Zimmermann H.J., 1978, Fuzzy programming and linear programming with several objective functions, Fuzzy Sets and Systems, 1, 45-55.