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# Synthesis of Combined Heat Exchange Network and Utility Supply Chain

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This paper involves the development of an integrated supply chain superstructure that describes the holistic synthesis of the heat demand of multiple co-located process plants within a geographical area and their associated utility supply chains. The integrated superstructure comprises a set of feedstock supply nodes which connects a set of utility demand nodes through a set of feedstock/utility transportation modes. Different kinds of biomass and waste-based feedstocks, including seasonality associated with their availabilities, from which hot utilities can be generated, and different modes of transportation, are considered. The model also takes into consideration periodic variations in heat demand of the plants. The proposed integrated model is demonstrated on a preliminary hypothetical case study and the solution obtained shows that supply locations with relatively higher capacity were selected in the optimal supply chain network, despite having relatively higher unit cost and located furthest from the demand locations. In terms of transport mode, only road truck haulage was selected due to its relatively lower investment cost.

## 1. Introduction

In the process industry, heating and cooling are carried out to ensure that process stream temperatures reach set target values. Such heating/cooling may be achieved through heat exchange with process streams and/or hot/cold utilities. Utilities can either be purchased or generated onsite, in which case operating cost will be incurred (Sieder et al., 2009). Utility cost is among the major operating cost in production industries, typically are the next highest contributor to a plant's operating cost after cost of feedstocks (Sieder et al. 2009).
The building of industrial development zones (IDZs) is receiving attention lately because it offers opportunities for resource and energy sharing amongst players in the zone. IDZ also establishes a platform by which interactions among the nodes within the zone, and with other nodes outside the zone, can be monitored and controlled. For an IDZ that comprises a group of process plants where hot utilities are required within each plant, adopting a holistic approach for the integration of the heat demand of the various plants will be beneficial in minimizing overall total annual cost (TAC). Such integration, which can be regarded as Total Site Heat Integration (TSHI), has received much attention in the literature (Dhole and Linnhoff, 1993). Liew et al. (2013) adopted a graphical and numerical based approach to target the minimum utility required in a total site system. Ong et al. (2017), using a bio-refinery as a case study, adopted P-Graph framework to optimise total site heat demand. Chew et al. (2015) developed a methodology for improving Total Site Heat Integration using Pinch Technology. Čuček et al. (2015) developed the procedure and code, based on Mathematical Programming and Pinch Analysis (MP/PA), for the retrofitting of large-scale heat exchanger networks (HENs) operating under steady-state and dynamic conditions applied to refinery total site. Hong et al. (2019) adopted a transhipment type model to TSHI, while Liu et al. (2017) used a coal gasification process as a case study to illustrate TSHI. Based on the papers reviewed, it was found that there is a lack of research studies investigating the added benefits that would be obtained if a utility supply chain network based on biomass and wastes is integrated with the heat demand of the individual processes or plants in the Total Site.

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Considering the environmental impact, the use of biomass and waste to generate heat may be favourable (Egieya et al., 2018), but since biomass and waste supply points are decentralised, a key cost that would be incurred if biomass/waste is used as a heat source is the cost of the supply chain. This then leads to a review of some of the works that have been done in the supply chain network (SCN) optimisation. SCN optimisation has been applied to various scenarios, which include bioenergy networks. Amongst such applications include the work of Čuček et al. (2014), where regional biomass and bioenergy SCN was optimally integrated using mixed-integer linear programming (MILP), and the work of Mutenure et al. (2018), which developed a SCN that illustrates a distribution pattern for bioethanol and sugar production in South Africa. The SCN by Egieya et al. (2019) was aimed at combined heat and power production from biogas while considering the multi-period profile of the supply and production sides. It should be known that these SCNs did not consider in detail the nature of the demand zones in terms of their energy demand and capital cost. In scenarios where the location of biomass and waste-based feedstocks (utility sources) is offsite relative to an IDZ, integrating the heat demand of each of the individual zones (process plants) in the IDZ with the utility supply chain, will not only result in reduced overall TAC, but also give opportunities for a reduction of the environmental impacts associated with such integrated networks. This work aims to use an integrated SCN to optimally select biomass and waste sources and distribute utilities to satisfy the periodic heat demand of a group of co-located process plants. The proposed simplified SCN model comprises two levels, which are harvesting sites and demand zones.

## 2. Problem statement

The problem addressed in this paper can be stated as follows: Given a set of process plants, *P*, that are co-located within a geographical area or IDZ, with each plant having a set of hot process streams, *H*, and a set of cold process streams, *C*. The supply and target temperatures, as well as heat capacity flowrates of the hot and cold process streams are multi-period in nature, with the periods denoted by set, *S*. Given also, is a set of biomass and waste-based feedstocks, *M*, from which hot or cold utilities can be generated, and the distances between the location of each feedstock relative to the process plants. Other parameters given are, a set of transportation options, *R,* to move feedstock to site for utility generation, or transporting an already generated utility, a set of seasonal feedstock availability time periods, *T*, including seasonal cost per unit of feedstock, a set of feedstock transportation costs, tortuosity factors for distances between feedstocks and process plants and heat exchanger installation and area costs. The goal is to develop an integrated SCN that optimally distributes feedstocks for hot utility generation to each process plant within the IDZ, while simultaneously optimizing the heat demand, through HEN synthesis, of each process plant to ensure an overall minimized TAC of the combined network. Optimising the TAC of the heat demand of each plant independent of others will most likely lead to an overall sub-optimal network having a relatively higher environmental impact. The holistic synthesis approach also helps in obtaining an overall supply chain network that optimally satisfies the annual performance of the network, especially in the face of variations in feedstock availability and plants' process stream parameters. This implies that the sizes of the heat exchangers in the HENs are configured to accommodate specified variations optimally.

## 3. Methodology

The supply chain aspect of the integrated superstructure is modelled as a MILP while the HENs aspect is modelled as a mixed-integer non-linear programming (MINLP) model using the stage-wise superstructure of Yee and Grossmann (1990). The supply points in the supply chain, which are denoted by index *m*, can be regarded as agricultural/processing sites containing feedstocks (biomass and waste) that can be used to generate hot utility in the form of steam. The demand zones are denoted by index *p* with each having HENs to be optimized. Since the goal is to determine the optimal multi-period based distribution profile of feedstocks for utility generation between feedstock location and heat demand zones, the parameter $D_{m,p}$ is used to represent the distances between each supply and demand zones. In the model, agricultural seasons (denoted by index *t*) have their durations represented by the parameter $L_t$, to capture the length of each season, with feedstock costs varying from season to season. The other time domain, denoted by index *s* that contributes to the multi-periodicity of the integrated model is the fluctuation around some nominal values, of the supply/target temperatures and/or the flows of the process streams in one or more of the plants in the demand zones. Such fluctuations may be due to changes in season, changes in feedstock quality, changes in product demand, process upsets, etc. The duration of plant period *s* is represented by $L1_s$. In the case study of this paper, only changes in supply temperatures and stream flowrates were considered. It is worth stating that variations in stream parameters will lead to variations in utility demand across periods. This variation needs to be optimally integrated with the variations in feedstock availability due to changes in seasons. This then brings to the fore, the need for a robust integrated superstructure that simultaneously optimizes the competing variables.

The supply chain component of the integrated network comprises conversion factors that indicate the quantity of hot utility that can be generated from biomass and waste, cost of feedstock, transport cost coefficients and logical constraints to ensure that capacity of each supply is not exceeded while satisfying heat demand of each plant for each period of operation. Eq(1) illustrates the cost contribution $SCN^{cost}_{m,p,r,t,s}$ of the supply chain to the integrated model's objective, where index *r* stands for the transportation options. The first three terms in Eq(1) quantify the cost of transport, while the last term considers the cost of feedstock. Transport cost comprises fixed cost distance related variable investment cost, and capacity and distance related variable transport cost that accounts for any variable costs associated with the network such as vehicle maintenance and fuel.

$$SCN^{cost}_{m,p,r,t,s} = \left[T^{FC}_r + tf_r.\tau_r.T^{VC}_r.D_{m,p}\right].\frac{x_{m,p,r,s,t}}{\frac{\eta \cdot LHV_m}{N_{hours}}} + T^{IC}_r.\tau_r.z_{m,p,r}.D_{m,p} + c^{Feed}_{m,t}\cdot\frac{x_{m,p,r,s,t}}{\frac{\eta \cdot LHV_m}{N_{hours}}}, \quad \forall m \in M;\ p \in P;\ r \in R;\ t \in T;\ s \in S \tag{1}$$

In Eq(1), $T^{FC}_r$ is the fixed cost factor (in $/kg) and is multiplied by each transport link's capacity $x_{m,p,r,s,t}$ (in kW), and converted to mass to account for the quantity of material that would be loaded and unloaded. The conversion to mass is done by dividing with parameters that account for combustion efficiency of biomass, $\eta$, and lower heating value of feedstock, $LHV_m$ (in kWh/kg), and assumed the operating time of the conversion facilities, $N_{hours}$ (in h/y). The terms used to convert to mass in Eq(1) are also multiplied by the transport variable cost $T^{VC}_r$ (in $/(kg·km)), the straight-line distance, $D_{m,p}$ (in km) between supply location *m*, and demand location *p*, and a tortuosity factor, $\tau_r$, which accounts for the actual distance travelled on the link, and return trip factor, $tf_r$, which accounts for costs incurred upon return to the supply zones after delivery. Tortuosity factor and straight-line distance are used to scale the investment cost factor, $T^{IC}_r$ (in $/km), which is then multiplied by the binary variable, $z_{m,p,r}$. The binary variable is used to indicate the existence, or otherwise, of a link between a supply and demand location through transport mode *r*. The last term, $c^{Feed}_{m,t}$ in Eq(1), which is the unit cost of feedstock *m* in season *t* (in $/kg), is also multiplied by the conversion terms to express in mass quantity.
Eq(2) is a logical constraint to ensure that all demands are satisfied within the limit of available supply capacities in all time periods *t* and *s*.

$$\sum_{p\in P}\sum_{r\in R} x_{m,p,r,s,t} \le a_{m,t}\cdot\frac{\eta \cdot LHV_m}{L1_s \cdot L_t \cdot N_{hours}}, \qquad \forall m \in M;\ t \in T;\ s \in S \tag{2}$$

Eq(2) ensures that summing all quantities of feedstock/utilities, $x_{m,p,r,s,t}$, shipped between supply *m* and plant, *p*, using any of the transport mode *r*, for each season *t*, and period *s*, gives a quantity that is less than or equal to the capacity of supply location $a_{m,t}$ (in kg/y). This is also converted to mass using the same conversion factor as in Eq(1). Eq(3) ensures that the total quantity of feedstock/utilities, $x_{m,p,r,s,t}$, shipped from supply *m*, using transport mode *r*, is greater than or equal to the quantity of hot utility demand $b_{p,t,s}$ (in kW) at each plant *p* while ensuring that each demand at each period of operation is satisfied considering the time period at which feedstock is available.

$$\sum_{m\in M}\sum_{r\in R} x_{m,p,r,s,t} \ge b_{p,t,s}, \qquad \forall p \in P;\ t \in T;\ s \in S \tag{3}$$

Eq(4) is another logical constraint which has the binary variable $z_{m,p,r}$. This variable is unique for each connection between a supply *m*, plant *p*, transport mode *r*, season *t*, and plant operational period *s*. It indicates the upper bound for the quantity of feedstock/utility that can be shipped in each transport link.

$$x_{m,p,r,t,s} \le a_{m,t}\cdot z_{m,p,r}\cdot\frac{\eta \cdot LHV_m}{L1_s \cdot L_t \cdot N_{hours}}, \qquad \forall m \in M;\ p \in P;\ r \in R;\ t \in T;\ s \in S \tag{4}$$

Eq(5) relates the supply chain component of the model to the quantities of heat demand in the HENs, $q_{p,i,j,k,t,s}$ (in kW), at each plant *p* and for each hot utility stream *i*, cold stream *j*, in temperature location *k* of the HEN superstructure, and season *t* and plant operational period *s*.

$$b_{p,t,s} = \sum_{i\in H}\sum_{j\in C} q_{p,i,j,k=1,t,s}, \qquad \forall p \in P;\ t \in T;\ s \in S \tag{5}$$

The objective function, shown in Eq(6) also connects the supply chain and the HEN. The first three terms in this equation relate to HEN cost, while the last term has to do with the supply chain cost. It is worth mentioning that since the HENs are multi-period, the maximum area approach for sizing heat exchangers areas $AX_{p,i,j,k}$ ($m^2$), as used by Verheyen and Zhang (2006), and the multiple periodic weighting approach as used by Isafiade et al. (2016) are also used in this paper. In Eq(6), which is the TAC objective of the combined network to be minimised (in \$/y), all first three terms are summed over all process plants, *p*. $A_p^F$ in Eq(6) represents annualization factor (in y$^{-1}$), $C_p^F$ represents fixed heat exchanger cost (in \$), $y_{p,i,j,k}$ represents binary variable which indicates the existence or otherwise of a heat exchanger in plant *p*, $A_p^C$ represents heat exchanger area cost (in \$/m$^2$), $A_p^E$ represents heat exchanger area cost exponent, and $C_{p,j,t}$ represents cost per unit of cold utility (in \$/kW).

$$\min TAC = \sum_{p\in P}[A_p^F\left\{C_p^F.\sum_i\sum_j\sum_k y_{p,i,j,k} + A_p^C.\sum_{i\in H}\sum_{j\in C}\sum_{k\in ST}[AX_{p,i,j,k}]^{A_p^E}\right\} + \sum_{i\in H}\sum_{j\in C}\sum_{k\in ST}\sum_{t\in T}\sum_{s\in S} L1_s \cdot L_t \cdot C_{p,j,t}\cdot q_{p,i,j,k,t}] + \sum_{m\in M}\sum_{p\in P}\sum_{r\in R}\sum_{t\in T}\sum_{s\in S} SCN_{m,p,r,t,s}^{cost}, \quad (6)$$

$$\forall m \in M;\ p \in P;\ r \in R;\ i \in H;\ j \in C;\ k \in ST;\ t \in T, s \in S$$

The minimisation of Eq(6) will give a network having the minimum TAC, and this involves the shipping of optimal quantities of feedstock for hot utility, through the most economical transport route, to meet heat demand in an optimal way in all operational periods for the process plants. The optimal network will also ensure that the selected heat exchangers are optimally sized despite variations in operational periods. The developed integrated model was solved using DICOPT in General Algebraic Modelling System (Rosenthal, 2012).

## 4. Case study

The case study considered involves three process plants, three feedstock locations, and three transportation options, connecting each feedstock location to each process plant. The transportation modes (truck, railway and pipeline) are considered. Each of the process plants, which has two hot and two cold process streams, can be served by the cold utility available on site. Hot utilities for each of the plants can be generated from any of the available feedstocks at the demand or supply locations. The integrated model, which is an MINLP, comprises 1,792 single equations, 2,602 continuous variables and 162 discrete variables. In the HENs data of each of the process plants, the variation in stream supply temperatures ($T^s$), and flowrates were assumed to have a night and day profile, of equal durations, and this was modelled as two periods of operations (P1 and P2).

*Table 1: Stream data for all plants in the day period*

| Plant | Hot stream | $T_i^s$ (°C) | $T_i^t$ (°C) | $FCP_i$ (kW/°C) | $h_i$ (kW/(m$^2$· °C)) | Cold stream | $T_j^s$ (°C) | $T_j^t$ (°C) | $FCP_j$ (kW/°C) | $h_j$ (kW/(m$^2$°C)) |
|---|---|---|---|---|---|---|---|---|---|---|
| | HU, 1 | 680 | 680 | 0 | 5 | C1, 1 | 420 | 650 | 15 | 1 |
| 1 | H1, 1 | 660 | 370 | 10 | 1 | C2, 1 | 360 | 500 | 13 | 1 |
| | H2, 1 | 600 | 370 | 20 | 1 | CU, 1 | 300 | 320 | 0 | 1 |
| | HU, 2 | 450 | 450 | 0 | 4.8 | C1, 2 | 303 | 408 | 20 | 1.6 |
| 2 | H1, 2 | 453 | 333 | 30 | 1.6 | C2, 2 | 363 | 413 | 40 | 1.6 |
| | H2, 2 | 433 | 303 | 15 | 1.6 | CU, 2 | 293 | 313 | 0 | 1.6 |
| | HU, 3 | 453 | 453 | 0 | 0.1 | C1, 3 | 303 | 398 | 25 | 0.1 |
| 3 | H1, 3 | 433 | 333 | 20 | 0.1 | C2, 3 | 308 | 373 | 30 | 0.1 |
| | H2, 3 | 373 | 333 | 80 | 0.1 | CU, 3 | 283 | 288 | 0 | 0.1 |

For the day period, inlet stream temperatures are the nominal values, while for the night period, they are 20 °C below the nominal values. Stream data for plants 1, 2 and 3 for the day period are shown in Table 1. In this table, $T^t$ is the target temperature of hot *i* and cold stream *j*, *FCP* is heat capacity flowrate, HU is a hot utility, CU is a cold utility, while *h* is heat transfer coefficient. For seasonal availability of feedstocks in the supply node of the superstructure, three seasons of fractional yearly durations 0.25, 0.5 and 0.25 were considered (S1, S2 and S3). Table 2 shows the feedstock types, cost and availability. It is assumed that the conversion efficiency of biomass to steam is 80 % and 8,160 h/y is operating time ($N_{hours}$). Table 3 further shows transport cost parameters; Table 4 shows distances between each supply and demand locations.

Figure 1a shows the optimal integrated SCN, which includes quantities of feedstock shipped from supply to demand locations. In this integrated SCN, which has a TAC of 3,152,445 \$/y, the quantity of feedstock transported (represented as hot utilities) for each agricultural season and plant period of operations, are shown. The supply chain component of the integrated network has a transport cost comprising an investment cost of 1,250,950 \$ and an operating cost of 64,802 \$/y.

*Table 2: Feedstock types, cost and capacity*

| Supply | Feedstock | | Season 1 | | Season 2 | | Season 3 | |
|---|---|---|---|---|---|---|---|---|
| | | LHV$_m$ (kWh/kg) | Cost ($/kg) | Capacity (×10$^6$ kg) | Cost ($/kg) | Capacity (×10$^6$ kg) | Cost ($/kg) | Capacity (×10$^6$ kg) |
| Supply 1 | Corn stover | 4.63 | 0.024 | 0.4 | 0.022 | 0.15 | 0.027 | 0.6 |
| Supply 2 | Glycerin | 4.75 | 0.400 | 500 | 0.450 | 5,000 | 0.250 | 50 |
| Supply 3 | Wood | 4.28 | 0.050 | 0.6 | 0.030 | 0.1 | 0.070 | 1 |

*Table 3: Transportation options cost parameters*

| Transport Mode | Transportation specific parameter | | | | |
|---|---|---|---|---|---|
| | $T_r^{FC}$ ($/t) | $T_r^{VC}$ ($/(t·km)) | $T_r^{IC}$ ($/km) | $\tau_r$ | $tf_r$ |
| Truck | 2 | 0.09 | 5,000 | 1.27 | 2 |
| Railway | 5 | 0.007 | 50,000 | 1.1 | 2 |
| Pipeline | 0 | 0.0001 | 1.5·10$^6$ | 1.27 | 1 |

*Table 4: Average distances between supply and demand locations in km*

| | Plant 1 | Plant 2 | Plant 3 |
|---|---|---|---|
| Supply 1 | 25 | 26 | 27 |
| Supply 2 | 52 | 50 | 51 |
| Supply 3 | 20 | 21 | 19 |

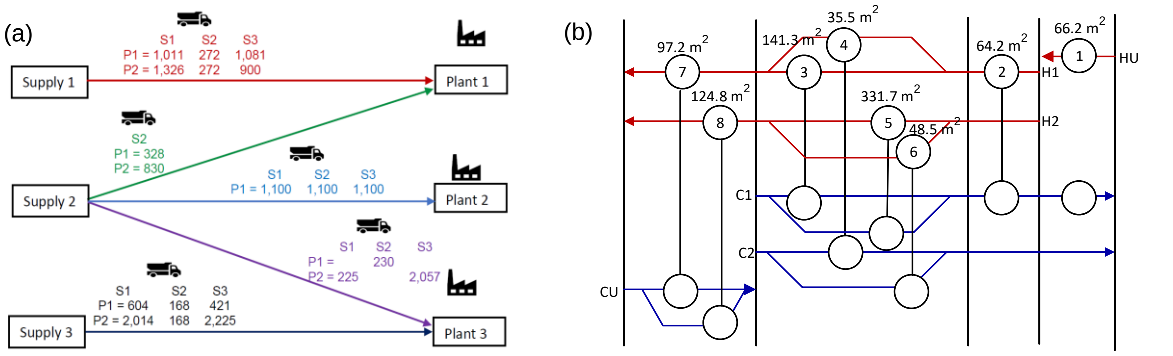


*Figure 1: (a) Supply chain showing quantity of utility shipped between supply and demand, (b) HEN for plant 1*

The three plants, which receive the hot utilities, have a combined investment cost of 313,842 $ for the heat exchangers, and an operating cost of 1,522,851 $/y for hot and cold utilities. Of the three plants' operating costs, hot utilities cost 1,451,277 $/y, which is the same as the total cost of feedstocks selected (i.e. raw materials only), while cold utility cost 71,573 $/y. In Figure 1a, supply 1 (corn stover) supplies only plant 1 in all three seasons. The same applies to supply 3 (wood), which supplies only plant 3 in all three seasons. On the other hand, supply 2 (glycerine) supplies feedstock for utility generation to all three plants. It supplies plant 1 only in season 2, while it supplies plants 2 and 3 in all seasons. Although the feedstock from supply 2 has the highest unit cost in all seasons, as well as being located furthest from all demand points, it still supplied the highest quantity of feedstock because it has the biggest feedstock capacity of all the supply locations. This implies that supply capacity for the given hot utility demand of the plants has a bigger influence on the integrated SCN cost. In terms of the periodic heat demand by the plants, Figure 1a shows that plant 1 receives hot utility in periods 1 and 2, while plant 2 only receives hot utilities in period 1. Plant 3 receives hot utilities in both periods 1 and 2, but the hot utilities are coming from supply 2 to plant 3 are delivered in season 2 in period 1 and in seasons 1 and 3 to period 2. A notable observation from the optimal solution of Figure 1a is that the HEN configuration in plant 2 is such that in period 2 heat demand is fully satisfied through process heat recovery. This was done to ensure that an optimal network is obtained at the integrated SCN level, rather than just at the level of individual HENs. In the HENs, plants 1 and 2 both have eight heat exchangers each, while plant 3 has 7 heat exchangers. The HEN for plant 1 is shown in Figure 1b. In terms of transport mode, road haulage by truck is the option selected. This is because the truck has the lowest investment cost, and this is the cost that has the most significant influence on transport mode cost contribution to the integrated SCN's TAC.

## 5. Conclusions

This paper has presented an integrated model which combines a supply chain of utility-generated from biomass and waste-based feedstock with a periodic heat demand of multiple co-located process plants. The integrated model, which is an MINLP, considers the seasonality associated with the availability of the feedstock. The optimal solution of the combined superstructure selects the optimal quantity of feedstock to be shipped from supply points to demand locations using the best mode of transport. Based on the case study considered, all supply locations and feedstocks are selected for shipment, but supply 2 is most favoured because it has the largest capacity. The most dominant cost in the solution obtained is the annual operating cost of the HEN, followed by the investment cost of the supply chain component of the integrated model. Road haulage was the only transport mode selected due to its relatively low investment cost. Future work will consider using more detailed cost correlations for the investment, variable and fixed costs, and better representation of the actual distances between supply and demand locations. More options of feedstocks, including fossil-based, which will be regarded as being centrally located, will also be considered. To have a more robust and flexible network, interplant heat integration and environmental impact of the network, will finally be considered.

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