Heating and cooling networks design algorithm for site wide energy integration

***A. Farhat*[a], *A. Zoughaib*[b], *K. El Khoury*[c]**

[a.] *MINES ParisTech, PSL Research University, CES -Centre d'efficacité énergétique des systèmes, Z.I. Les Glaizes – 5 rue Léon Blum 91120 Palaiseau, France. alaa.farhat@mines-paristech.fr*
[b.] *MINES ParisTech, PSL Research University, CES -Centre d'efficacité énergétique des systèmes, Z.I. Les Glaizes – 5 rue Léon Blum 91120 Palaiseau, France. assaad.zoughaib@mines-paristech.fr*
[c.] *Lebanese University, Faculty of Engineering, Roumieh, Lebanon. khalil.elkhoury@ul.edu.lb*

Abstract:
Heat integration is a widely used methodology to reduce industrial plants energy consumption, utility targeting and optimal configuration for heat recovery. Heat integration was extended to target several aspects such as heat exchangers synthesis or thermodynamic systems integration for heat recovery and valorisation. The total site heat integration (TSHI) method was introduced to recover post heat integration surplus heat in one or more plants plant by transporting it through tertiary steam mains to other plants, and reduce the overall energy consumption. Liquids represent as alternatives to steam, since they can emulate certain process fluids behaviour by changing temperature, which increases the heat recovery potential. In this paper, a first linear programming model based on the coupling of the TSHI method and exergy analysis is presented, this coupling helps specifying the networks and thermodynamic conversion systems that will enhance the overall exergy efficiency. Thermodynamic systems include heat pumps, absorption refrigeration cycles, organic Rankine cycles and cogeneration systems. A second model evaluates the proposed solutions economically. It considers energy transportation and conversion costs. It takes into consideration geographical positioning of plants to specify the type of networks (steam or liquid) routing, sizes of pipes and heat exchangers' surface area. The two models can be used in a two steps approach; meaning systems are specified then evaluated economically, or in a simultaneous approach. To illustrate the capabilities of this approach a case from the literature is studied.

Keywords:
Heat Integration, optimisation, total site analysis, heat transfer networks.

1. Introduction

Heat integration is a widely used method that allows heat recovery between different streams in an industrial plant, heat integration problems were usually solved using the pinch method introduced by Linhoff et Al. [1], or using Mixed integer linear programming (MILP), as proposed by Papoulias and Grossman[2]. To cover sub ambient cooling processes, exergy analysis was used to study the integration of refrigeration systems and later to integrate heat pumps. In most cases, after applying Heat Integration, surplus heat and/or energy deficit remain. Linhoff and Dhole [3], to recover post heat integration surplus heat in a plant to supply the deficit in neighbouring plant, further extended the method; this practice is called the Total Site Heat Integration. TSHI was the basis for many methodologies that cover different aspect of heat integration of two or more neighbouring plants such as sudden plants shutdowns as in the work of Liew et Al. [4] and cogeneration as proposed by Bandhopadyay et Al. [5]. In many of the related works, tertiary heat networks present the means to accomplish heat recovery between plants, this is due to the complexity that a direct integration between streams belonging to different plants imposes such as stream compatibility and the various drawbacks of potential product leakage (security, environmental). Originally in the TSHI, any heat pocket in a generally heat deficient area (above the pinch point) was disregarded. Later, Rodera and Bagajewisc [6] proved that exclusion of those pockets limits the maximum amount of heat transfer between plants, in their approach to energy integration between multiple plans. This exclusion limits the heat exchange to an area created by the pinch points of different installations. Steam was proposed originally as a heat transfer medium since it has convenient installation costs and steam systems are widely adopted in industrial installations. Rodera and Bagajewisc[6] challenged the latter, by showing that liquid networks can achieve better heat recovery since they present a variable temperature while exchanging heat thus emulating streams behaviour and can be as economically interesting as steam in the long term.

This paper, covers the economical aspect of site wide energy integration by proposing a model that takes into consideration both energy and economical aspects of the heat transfer systems. A study of economic aspects imposes considering the geographical positioning of plants with respect to each other and a hydraulic modelling of the heat transfer systems.

The proposed hydraulic model is coupled to an exergy model developed by the authors of this paper. The methodology proposed is a two steps one using first solely the exergy model. The proposed integration scenarios are then considered for economic evaluation by using the hydraulic model coupled to the exergy model on a limited search space. This two steps approach allows having economically viable solutions while limiting the calculation time.

2. Exergy Model

The proposed model performs an exergy analysis to choose and specify the properties of any heat conversion system and heat transfer network that can use, post-heat integration, residual heat most effectively. The model is built as a transportation model, where each plant has temperature interval defined as in Papoulias and Grossman [5] with the option of refining temperature intervals to study more options such as heat conversion systems integration. The total number of intervals is denoted by *Nt*. Plants have the possibility to exchange with others via networks and to integrate conversion systems.

Fig. 1 shows an example of the model for a plant *p*, the intervals having the highest temperature has the smallest index, the interval is bounded by T_i and T_{i+1}, where $T_i > T_{i+1}$. In each interval, the residual heat is calculated. In case the interval has a surplus of heat, which can be cascaded to an interval having a lower temperature, transferred to a network, or to supply a heat conversion system's component e.g. a heat pump's evaporator. Conversely, the condenser of a heat pump or a network can supply an interval having a heat deficit. Intervals having the highest temperature T_h ($i=0$) have a default hot utility *Qh*. The temperature interval having the lowest temperature has a default cold utility T_c ($i=Nt$).

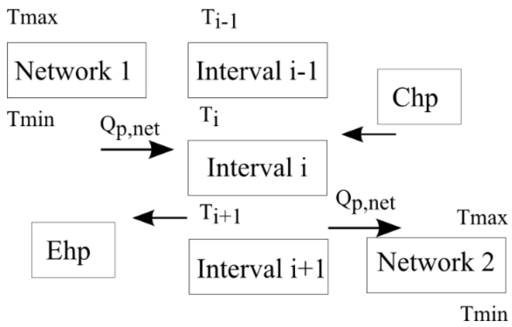

Fig. 1 Interaction of intervals with different energy systems in a plant p

In the case where interval have sub ambient temperatures, refrigeration systems *Qr* are allowed at each interval to remove any excess heat, refrigeration systems are vapor compression systems where the evaporator exchanges with the heat interval at its lower bound temperature T_{i+1} and the condenser exchanges with the surroundings having a temperature of T_a. Each of the systems has a consumed exergy rate, calculated as shown.

Table 1. Exergy consumption rates for default systems

System	Exergy consumption Rate
Default Hot Utility	$ExQh_p = (1 - T_a/Th_p) \times Qh_p$ (1)
Default Cold Utility	$ExQc_p = (T_a/Tc_p - 1) \times Qc_p$ (2)
Refrigeration systems	$ExQr_{p,i} = (T_a/T_{p,i+1} - 1) \times Qr_{p,i}$(3)

2.1 Energy Conversion systems modelling

2.1.1 Heat Pumps:

A heat pump (HP)supplies heat through its condenser to an interval *i* at a temperature *T*Chp greater than the interval's upper bound T_i, and extracts heat through its evaporator from another j at a temperature *T*Ehp lower than its lower bound T_{j+1}. The coefficient of performance (4) is calculated using a second law cycle efficiency η_{hp} and the Carnot ideal COP (calculated using temperatures at both its condenser and evaporator).

$$COP_{p,i,j} = \eta_{hp} \times (T_{Chp}/T_{Chp} - T_{Ehp}) \quad (4).$$

Where p denotes the plant housing the heat pump.

2.1.2 Organic Rankine Cycle

An Organic Rankine Cycle (ORC)absorbs heat through its evaporator to an interval *i* at a temperature T_{Eorc} lower than its bound T_{i+1}, and rejects heat through its condenser to the surroundings represented by the T_a (ambient temperature). In the same manner as for HP, the ORC efficiency (5) is calculated using a second law efficiency and Carnot cycle efficiency.

$$\eta orc_{p,i,j} = \eta_{orc} \times (T_{Eorc} - T_a)/T_{Eorc} \quad (5)$$

2.1.3 Absorption Chillers

Absorption Chiller are represented as an ideal Carnot engine and an ideal Carnot heat pump cascaded with each other where the engine receives heat and produces mechanical work to feed the heat pump. A second law efficiency is assumed to derive real systems behaviour (6). The system withdraws heat through the generator, at a temperature T_{Gac} lower than the lower bound T_{i+1} of an interval *i* and withdraws heat through its evaporator at a temperature T_{Eac} lower than the lower bound T_{j+1} of another interval *j*.

$$COPabs_{p,i,j} = \eta_{abs} \times (T_{Gac}/(T_{Gac} - T_a)) \times (T_a/(T_a - T_{Eac})) \quad (6)$$

Table 2. Exergy consumption/valorization of heat conversion systems

System	Thermodynamic Relation	Exergy consumption/valorization
HP	$Chp_{p,i,j} = Ehp_{i,j} \times COP_{i,j}/COP_{i,j} - 1$(7)	$Elec_{p,i,j} = Chp_{p,i,j}/COP_{i,j}$(10)
ORC	$Eorc_{p,i,j} = Corc_{p,i,j} \times (1 - \eta_{orc,i,j})$(8)	$W_{p,i,j} = Eorc_{p,i,j} * \eta orc_{p,i,j}$(11)
AC	$Eabs_{p,i,j} = Gabs_{p,i,j} \times (COP_{absi,j})$(9)	

2.2 Networks

Networks transfer heat from a plant to another; the only restriction for networks is a necessary temperature difference between the stream's temperature and the network's temperature.

In general if a network, having *Tmax* as its higher temperature and *Tmin* for its lower one, is supplying heat, represented by $Q_{net,p}$, to a plant, at an interval of T_i, the following is respected

$$Tmax \geq T_{p,i} + \Delta T_{res,i} \quad (12).$$

$$Tmin \geq T_{p,i+1} + \Delta T_{res,i} \quad (13).$$

In case the same network is withdrawing heat, represented by $Q_{p,\mathrm{net}}$, at a higher interval of T_{i-1} for instance, then the following is respected

$$Tmax \leq T_{p,i-1} - \Delta T_{res,i-1} \quad (14).$$

$$Tmin \leq T_{p,i} - \Delta T_{res,i-1}. \quad (15).$$

Since steam networks maintain a unique temperature through a heat exchange then *Tmax* is equal to *Tmin* ; (12) to (15) above are always respected.

2.3 Objective Function

The objective function is the sum of exergy consumption, which is to minimize. By minimizing exergy consumption the linear programme will find the optimal placement of heat transfer networks and heat conversion systems.

$$Ex = \sum_{p=1}^{Pl} ExQh_p + ExQc_p + \sum_{p=1}^{Pl} \sum_{i,T(i+1)<Ta}^{Nt} ExQr_{p,i} + \sum_{p=1}^{Pl} \sum_{i=0}^{Nt} \sum_{j=i+1}^{Nt+1} Elec_{p,i,j} - \sum_{p=1}^{Pl} \sum_{i=0}^{Nt} \sum_{j=i+1}^{j=Nt+1} W_{p,i,j}. \quad (16).$$

2.4 Output of the exergy model and link with the hydraulic model

The output of the exergy model specifies the properties of each system:

- For networks; its type: steam or liquid network, its operating temperatures and capacity.

- For heat conversion systems: capacity and temperature at each exchanger, electrical power needed by heat pumps and electrical power produced by organic Rankine cycle

The hydraulic model needs a principal variable as input, which is the mass flow rate in pipes. The variable can be found in $Q_{p,net}$ and $Q_{net,p}$, which indicate the heat transferred from a plant to network or vice versa. The medium of heat transfer physical properties and temperature allow calculating the mass flow rate as shown in (17) and (18).

$$\dot{m} = Q/(\Delta h). \quad (17).$$

Where, Δh is the enthalpy variation during heat transfer. In the case of a liquid network

$$\Delta h = Cp \times T \quad (18).$$

Where *Cp* is the heat capacity and ΔT is the network temperature difference, in the case of a steam network Δh is the latent heat. In Fig. 2, the algorithm explains the first step that involves only the exergy model and the second step that uses the same exergy model with a restricted research space to the previously determined solutions and combines it with the hydraulic model.

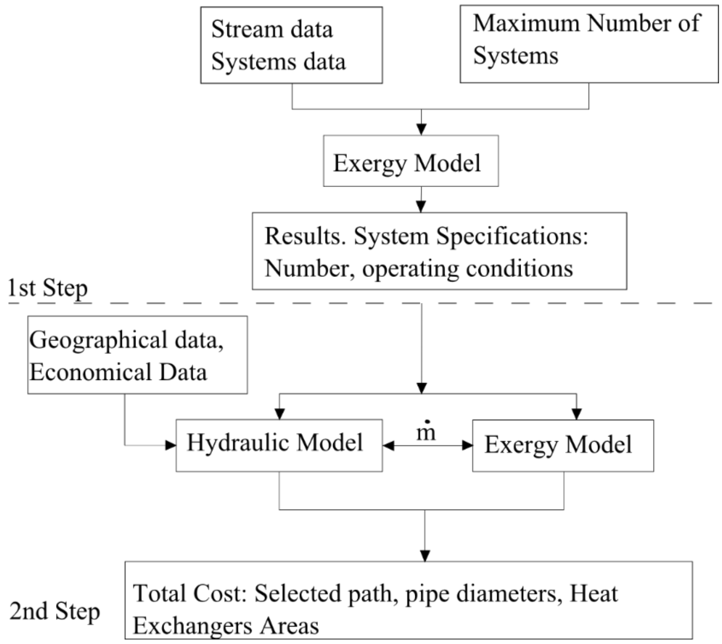

Fig. 2. Algorithm connecting the different models.

3. Hydraulic Model

The hydraulic model takes into consideration geographical positioning of plants, and the available paths for laying down pipes needed to accomplish heat transportation. This set of data, where plants geographical positions and path intersection create a set of nodes, allows the construction of a closes network.

3.1 Networks Construction

3.1.1 Pipes and routing

An example of available paths is as shown in Fig. 3, intersection between paths create nodes, which represent potential pipe junctions. Each path can have limitations such as maximum pipe size, or maximum pipe number, pipe length corresponds to the individual path length.

To allow for selection according to pipe diameter, each path can have a series of pipes having different diameters passing through it as shown in Fig. 4, but only the one proving its economical worth remains.

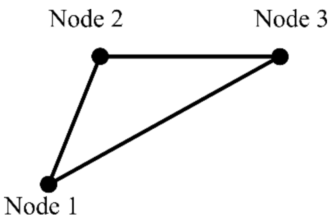

Fig. 3 Pipe routing

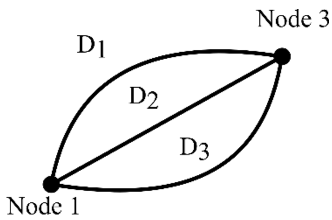

Fig. 4 Pipe diameter possibilities on a path

3.1.1.2 Steady state mass conservation at nodes

In general at a network, plants that are connected to the network will be injecting or withdrawing heat from or to the network via the nodes. A node can host one plant or more. The total mass flow rate from and to plants at a node *n* is.

$\dot{m}_{net,m,plants} = \sum_{p=1}^{Pl} \dot{m}_{p,net} - \sum_{p=1}^{Pl} \dot{m}_{net,p}$ (19)

Where a plant *p* must be connected to the node *n*.

Since a node n is connected to other nodes via paths, and the steady state mass conservation applies then the mass gained from plants connected to n will be transferred to other nodes, conversely if plants connected to n are withdrawing heat then the amount withdrawn must be compensated with mass transferred from other nodes. Therefore:

$$\dot{m}_{net,m,plants} = \dot{m}_{net,m,routes} \quad (20)$$

To limit the number of variables, paths indices are arranged by ascending nodes indices, meaning a path connecting two nodes m and n is identified by $m \to n$, if $m < n$ and the path $n \to m$ does not exist. Therefore the mass flow leaving m towards n is defined by $\dot{m}_{net,m \to n}\ where\ m < n\ and\ \dot{m}_{net,m \to n} \geq 0$ in case the mass flow was leaving n towards m in path $m \to n$ then $\dot{m}_{net,m \to n} \leq 0$.

At the node m, the summation of possible exchange with other nodes is as follows

$$\dot{m}_{net,m,routes} = \sum_n \dot{m}_{net,m \to n}\,(m < n) - \sum_o \dot{m}_{net,o \to m}\ (o < m) \quad (21)$$

3.1.1.2 Pressure drop equilibrium in loops

Three or more nodes define a loop in a network. In Fig. 3, if a certain mass flow is going from node 1 towards node 3, it can go directly from 1 to 3, or go from 1 to 3 by passing through 2, in this case the flow in the two paths is considered to be parallel and the following applies.

$$H_{1 \to 3} = H_{1 \to 2} + H_{2 \to 3} \quad (22).$$

If a network consists of one or more loops, each loop represents a set of nodes, where a start node and an end node are selected. The pressure in the path directly connecting the start node to the end node should be equal to the sum of pressure drops of the paths connecting the start node to the end node via other nodes. This creates a set of equations applying the Kirchhoff law to all loops. Therefore if m and n are the start and end node respectively.

$$H_{m \to n} = \sum_{o=m,r} H_{o \to r}\ (o < r\ \ and\ o, r\ \in loop) \quad (23)$$

3.1.2 Pipe diameter sizes

The pipe diameter sizes set is decided using specifications of conventional pipes such as steel or iron pipes. However, a predefined set that is compatible with the heat flow calculated by the exergy model limits the search space. This helps avoiding large computation time.

3.1.3 Practical constraints

For cases where pipe size might be restricted or no pipes are allowed at all, paths properties can be amended to cater for those restrictions. Other cases include large installation costs due to specific local requirement (river crossings, accommodation within other existing utilities), such costs can be added uniquely to any of the proposed paths.

3.2 Hydraulic Aspects

3.2.1 Networks using liquids:

Since the proposed model is linear and friction in pipes is calculated using non-linear equations, a linearization, using the friction factor based on Colebrook [7] approximation for liquids, is proposed.

Friction in pipe:

$$H = f\frac{lV^2}{D \times 2g} \quad (24)$$

Pumping power:

$$P = f\frac{lV^2}{D * 2g} \times V \times A \quad (25)$$

Friction factor according to Colebrook-White:

$$\sqrt{f} = -2\log(\frac{\varepsilon}{3.7D_h} + \frac{2.51}{Re\sqrt{f}}) \qquad (26)$$

For the linearization to be accurate it is piecewise. The velocity range is divided into different consecutive intervals having different ranges. The range of the interval is defined by the curvature of the correct function; larger curvature necessitates smaller interval ranges, while flatter regions can be represented using large intervals.

3.2.2 Networks Using Steam:

In a similar manner, the Unwin formula [8] is used for the calculation pressure drop in steam. Although the Unwin formula has some inaccuracies in some cases but it is widely used for the calculation of steam pressure drop in pipes. The model however can accept other formulas for the calculation of pressure drops.

$$dp = 0.6753106\, \dot{m}^2 \times l \times (1 + 91.4/D) / \rho D^5 \quad (27)$$

Linearization is done in a similar way to pipes having single-phase flow.

3.3 Mathematical formulation

3.3.1 Velocities in pipes

First equations to be shown are those showing the linearization intervals for each branch. First, a set of indices are presented to explain the various parameters. The formulation applies to all type of networks.

Where,

$Vmin_v$, lower bound velocity for interval v

$Vmax_v$, upper bound velocity for interval v

$V_{net,v,d,m\rightarrow n}$ Variable representing the velocity in a pipe of a diameter d connecting m to n, in the network net, limited by the interval v, hence:

$$Vmin_v \le V_{net,v,d,m\rightarrow n} \le Vmax_v \qquad (28).$$

Fig. 4 explains the idea, the path between node 1 and node 2 can have different pipe diameters. For each pipe different fluid velocities can be encountered, between these entire possibilities only one shall be chosen.

For this an integer variable is assigned for each velocity interval and for all the diameters this variable is $Vint_{net,v,d,m\rightarrow n}$., (28) becomes:

$$Vint_{net,v,d,m\rightarrow n} \times Vmin_v \le V_{net,v,d,m\rightarrow n} \le Vint_{net,v,d,m\rightarrow n} \times Vmax_v \qquad (29).$$

When $Vint_{net,v,d,m\rightarrow n}$=0, $V_{net,v,d,m\rightarrow n}$ will be set to 0, since it will be bounded by 0 and when $Vint_{net,v,d,m\rightarrow n}$ is equal to 1,it could be anywhere between $Vmin_v$ and $Vmax_v$. To choose only one pipe having a unique velocity the sum of the corresponding integer variables for one path (m →h n) should be 1 therefore:

$$\sum_d \sum_v Vint_{net,v,d,m\rightarrow n} \le 1 \qquad (30)$$

and,

$$\sum_d \sum_v V_{net,v,d,m\rightarrow n} \times \rho \times \pi D^2/4 \le \dot{m}_{net,m\rightarrow n} \qquad (31)$$

3.3.2 Pressure drop in pipes

The equations representing the linearization of the original pressure drop are presented here below. The equations are of the general form (32):

$$H_{v,n,d,i\rightarrow j} = A_{v,d} \times V_{net,v,d,m\rightarrow n}g + B_{v,d} \quad (32).$$

Where A and B represent the coefficients of linearization. However in (29) if $Vint_{v,n,d,m,n}$ is equal to 0 then $V_{net,v,d,m\rightarrow n}$ is set automatically to 0 and $H_{net,v,d,m\rightarrow n}$ will be equal to B, for this (32) becomes

$$H_{net,v,d,m\rightarrow n} = A_{v,d} \times V_{net,v,d,m\rightarrow n} + B_{v,d} \times Vint_{net,v,d,m\rightarrow n} \quad (33).$$

In (33) when *V* and *Vint* are equal to 0 then H will be equal to 0 as well.

3.3.3 Path elimination

In an optimal designs some paths can be excluded i.e. having no flow, in the case where one of those paths belongs to a loop, a no flow condition will not cause any pressure drop inside the pipe. As an example in (22) if the paths $H_{1\rightarrow 2}$ and $H_{2\rightarrow 3}$ are eliminated for economic reasons, a no flow condition will cause $H_{1\rightarrow 2}$ to be null, hence blocking any possible solution. To overcome this each pipe has the possibility to emulate a closed valve. Meaning a singular and very large pressure drop coefficient H_S can be added to each pipe leading to emulate an orifice that will let through a very small amount of mass flow in the pipe.

$$H = (H_s + f)\frac{lV^2}{D\times 2g} \quad (34).$$

In this case, the Kirchhoff loop law still apply and this path is eliminated in the results post treatment.

3.4. Heat Exchangers

Heat exchangers are installed between individual streams denoted by *s* and the tertiary networks. Heat exchangers area is calculated using (35)

$$A_{net,p,s,i,j} = Q_{net,p,s,i,j}/(LMTD_{net,p,s,i,j} \times U_{net,s}) \quad (35).$$

Where Q is the heat flow and LMTD is the logarithmic mean temperature difference. The temperatures used in the LMTD calculation (36) are the networks temperatures *Tmax* and *Tmin* and the temperatures of the stream's at the exchange $T_{p,s,i}$ and $T_{p,s,j}$. where $i<j$ and $T_{p,s,i}$ and $T_{p,s,j}$ are bounded by the stream's inlet and outlet temperatures $T_{s,in}$ and $T_{s,out}$ as shown Fig. 5. Noting that a minimum temperature difference ΔT between streams and networks is respected.

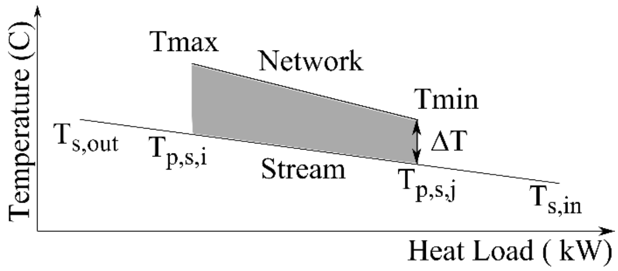

Fig. 5 Heat exchange between a stream and a network

$$LMTD_{net,p,s,i,j} = \left(\text{Tmax} - T_{p,s,i}\right) - (\text{Tmin} - T_{p,s,j})/\ln(\left(\text{Tmax} - T_{p,s,i}\right)/(\text{Tmin} - T_{p,s,j})) \quad (36).$$

Since the heat flow in the heat exchangers is the same circulating in the network then (37) and (38) are needed.

For cold streams

$$Q_{net,p} = \sum_{p=1}^{Pl} \sum_{s}^{Sp} \sum_{i} \sum_{j} Q_{net,p,s,i,j} \quad (37)$$

For hot streams

$$Q_{p,net} = \sum_{p=1}^{Pl} \sum_{s}^{Sp} \sum_{i} \sum_{j} Q_{p,net,s,i,j} \quad (38).$$

4. Cost Model

To determine the economic feasibility of heat transfer networks between multiple plants a cost model is built. The model takes into consideration the installation and operational costs of networks. However the operational costs and the investment costs need to be differentiated, since operational costs are cumulated over a period and investment costs can be paid in one lump or through instalments.

4.1 General

Equation (39) represents the general form of the cost model.

$$Cost = Capex + \sum_{t=0}^{TOR} NOH_y \times Opex_y \times (\frac{1}{1+ir})^y \qquad (39)$$

Capex is the sum of all the investment costs and Opex is the sum of all the operational costs according to the year. The goal is to minimize this function, when minimized it will give the optimal configuration of the needed number of networks and their specifications. The TOR is the integration period of the operational cost; this parameter will impact the relative weight of the investment costs versus the operational costs. A large TOR will favour investments that reduce the operational costs.

4.2 Piping cost

Piping costs comprise of the cost of pumping costs, maintenance and installation costs.

4.2.1 Pumping cost

The pumping power is calculated using,

$$P_{total} = \sum_{v,n,d,i,j} P_{v,n,d,i \to j} \qquad (40)$$

The number of operating hours during the integration period and the cost of electrical energy in kWh are then multiplying the pumping power to obtain the pumping cost.

$$C_{\text{Pumping}} = \sum_{y=0}^{TOR} C_{electric} \times NOH_y \times P_{total}(\frac{1}{1+ir})^y \qquad (41)$$

4.2.2 Installation Cost

The installation costs are determined using the binary variables that determine the existence of networks and the chosen pipes costs (42). Pipes that are used to emulate closed valves are not counted.

$$C_{\text{Piping}} = \sum_{v,n,d,i,j} Vint_{v,n,d,i \to j} \times C_{pipe,v,n,d,i \to j} \qquad (42)$$

Here $Cost_{v,n,d,i,j}$represents the cost of each pipe depending on its size, physical properties, trenching, and location on site. A singular cost function allows for the inclusion of singular costs imposed by the topography and site properties.

4.2 Heat exchangers Costs

Heat exchangers cost represent a more difficult task since the cost function is not linear. However, this can be linearized piecewise with respect to the surface area. The same linearization process used to calculate pipes pressure loss is used. A heat exchanger consists of the sum of many different heat exchangers where the each one's area is bounded by an interval created by a minimum are and a maximum area.

$$A_{net,p,s,i,j} = \sum_{e=1}^{E} A_{net,p,s,i,j,e} \qquad (43)$$

The linearization imposes an equation of the form

$$C = VC \times A + FC \qquad (44).$$

Where VC is the variable cost and FC is the fixed cost of the exchanger, binary variables are mandatory to prevent having fixed costs being added to the cost function in the case where the heat exchangers area is 0.

$$Amin_e \times Aint_{net,p,s,i,j,e} \leq A_{net,p,s,i,j,e} \leq Amax_e \times A_{net,p,s,i,j,e} \qquad (45)$$

Since only one heat exchanger area range can be selected:

$$\sum_{e=1}^{E} Aint_{net,p,s,i,j,e} \leq 1 \qquad (46)$$

And the cost function becomes:

$$C_{exchanger,net,p,s,i,j,e} = VC_e \times A_{net,p,s,i,j,e} + FC_e \times Aint_{net,p,s,i,j,e} \qquad (47)$$

The total heat exchangers cost is:

$$C_{exchangers} = \sum C_{net,p,s,i,j,e} \qquad (48)$$

4.3 Utilities and thermodynamic systems cost

Utilities cost is calculated as a linear function of their capacity. Moreover, in certain cases operation and installation costs can differ with respect to the plants, hence different cost coefficients are used for each plant. In the case of organic Rankine cycles, the operation costs are negative since it generates power instead of consuming. In some cases a heat integration project could be a retrofit hence installation costs existing default utilities can be omitted in that case.

$$C_{u,installation} = \sum_{p=1}^{Pl}\Big[C_{Qh,p} \times Qh_p + C_{Qc,p} \times Qc_p + \sum_{i,T_{i+1}<T_a}^{Nt+1} C_{Qr,p} \times Qr_{p,i} + \sum_{i=0}^{Nt}\sum_{j=i+1}^{Nt+1}(C_{hp,p} \times Chp_{p,i,j} + C_{orc,p} \times W_{p,i,j} + C_{abs,p} \times Eabs_{p,i,j})\Big] \qquad (49)$$

$$C_{u,operation} = \sum_{y=0}^{TOR}\sum_{p=1}^{Pl} NOH_{y,p} \times \Big\{C_{heat,p} \times Qh_p + C_{elec,p} \times \Big[\big(T_a/Tc_p - 1\big) \times Qc_p + \sum_{i,T_{i+1}<T_a}^{Nt+1}\big(T_a/T_{p,i+1} - 1\big) \times Qr_{p,i} + \sum_{i=0}^{Nt}\sum_{j=i+1}^{Nt+1}(WElec_{p,i,j} - W_{p,i,j})\Big]\Big\} \times \left(\frac{1}{1+ir}\right)^y \qquad (50)$$

5 Case Study

In the THSI method non-monotonous parts of the GCC were excluded, in some examples this exclusion prevents finding the maximum possible heat transfer as shown by Rodera and Bagajewisc [6]. The same case used in [6] is evaluated economically using the proposed methodology to assess the feasibility of such networks. The results of the exergy model come in accordance with the original results of Rodera and Bagajewisc.

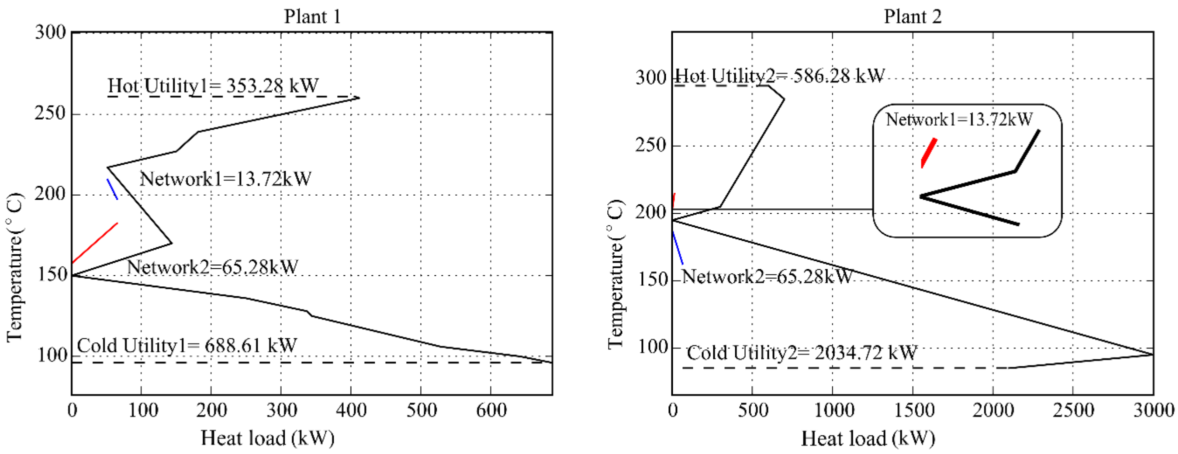

Fig. 6 GCCs of plants 1 and 2 showing the resulting networks

On this Fig. 6, the GCC of each plant is shown on which the networks are represented. The networks when withdrawing heat are shown in red and when supplying heat are shown in blue. Network 1 is installed just under the heat pocket in plant 1.

The output from the first model is used in the combined model. The distance between the plants is supposed to be 80 m. In a first simulation, the investment return time (TOR) is set to two years with a yearly interest rate of 6.7 %

The results show that the network 1 is not feasible. The main reason for the exclusion is the fact that network 1 will reduce the total utility capacity by 13.72 kW but it will have a cost implication on the second network since network 2 will resupply plant 1 the same heat amount. This double penalty leads to a non cost effective situation.

A second trial is performed where the investment return time (TOR) is increased to 3 years. In this case the network is kept. Tables 3 and 4 detail the technical and economical parameters of the scenario.

Table 3 Network properties

Network	Pipe Diameter (mm)	Tmax (°C)	Tmin (°C)	Exchangers area (m^2)
1	15	209.5	197.5	12
2	25	182.5	157.5	49

Table 4 Systems Cost

Network	Piping Costs ($)	Exchangers Costs[1] ($)	Capacity (kW)	Savings (kW)
1	13810	18380	13.72	13.72
2	15560	44242	65.28	51.5

[1]Exchanger cost function=5000 +700×A

The piping costs are almost the same due to the high temperature difference in network 2, which will reduce the required mass flow and hence the installation costs that are mainly similar for small piping. The estimated additional cost in network 2 due to the existence of network 1 is around 7200 $. So in total the 13.72 kW cost 39390 ($) or (2870 $/kW) in investment costs taking into consideration its effect on the heat exchanger cost in network 2. While network 2 costs 52600 $ or (1021 $/kW), while testing it without network 1. The findings above go in line with excluding heat pockets above the pinch in the grand composite curve (GCC) but it cannot be done a priori.

It can be remarked also that the location of the network can have an important effect on the costs. In this example the GCC show that network 1 cannot have a large temperature difference, since the slope of the heat pocket at plant 1 is high and can merely fit the network while respecting the temperature difference at both sides. While network 2 works with large temperature difference leading to relatively a smaller cost that network 1.

Practically, such networks imply the issue of using non-conventional fluids such as oils or water under pressure.

6. Conclusion

In this paper, a methodology that takes into account economical optimisation is presented. It is a second step to a methodology that was developed for energy or exergy targeting with the capacity of exploiting the energy properties of industrial plants. Combining the two methodologies helps having a preliminary economic assessment of site wide heat integration; the assessment's accuracy improves with the level of detail provided by the user, results are better verified to account to any imprecision induced by the linearization process. The case study shows that multiple aspects affect the study of networks installation, such as the possible location of the network in function of the different plants GCC's and utility size. Currently this algorithm provides an assessment of a solution generated by the exergy model; hence it is providing a feasible economic solution for this specific solution.

Nomenclature

A area, m^2
C cost, $/kW
Chp heat pump condenser, kW
Corc organic rankine cycle condenser, kW
Cp heat capacity, kJ/kg.K
D pipe diameter, m
Eabs absorption chiller evaporator, kW
Ehp heat pump evaporator, kW
Eorc organic rankine cycle evaporator, kW
f, fiction factor
Gabs absorption chiller generator, kW
H, head loss m
h, enthalpy kJ/kg
ir interest rate
L, distance m
m mass flow rate, kg/s
NOH number of operating hours
Nt, total number of intervals
P, pumping power kW
Pl, total number of plants
Q heat, kW
Re Reynolds number
Sp, total number of streams
T temperature, C
TOR, time of return
V velocity, m/s
U exchanger heat transfer coefficient, W/(m^2.K)

Greek Symbols

ε pipe roughness, m
η efficiency
ρ density, kg/m^3

Subscripts

d diameter
e exchanger area interval
i,j temperature indices
m,n nodes
net network
p plant
s stream
t time
v velocity interval
y, year

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