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Article

Total Site Heat Integration Considering Pressure Drops

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Abstract: Pressure drop is an important consideration in Total Site Heat Integration (TSHI). This is due to the typically large distances between the different plants and the flow across plant elevations and equipment, including heat exchangers. Failure to consider pressure drop during utility targeting and heat exchanger network (HEN) synthesis may, at best, lead to optimistic energy targets, and at worst, an inoperable system if the pumps or compressors cannot overcome the actual pressure drop. Most studies have addressed the pressure drop factor in terms of pumping cost, forbidden matches or allowable pressure drop constraints in the optimisation of HEN. This study looks at the implication of pressure drop in the context of a Total Site. The graphical Pinch-based TSHI methodology is extended to consider the pressure drop factor during the minimum energy requirement (MER) targeting stage. The improved methodology provides a more realistic estimation of the MER targets and valuable insights for the implementation of the TSHI design. In the case study, when pressure drop in the steam distribution networks is considered, the heating and cooling duties increase by 14.5% and 4.5%.

Keywords: Total Site Heat Integration; Pinch Analysis; pressure drops; utility distribution; pumping

1. Introduction

Pressure drop is an important factor to consider during a Heat Integration (HI) system design [1]. It is especially so with Total Site Heat Integration (TSHI) when distances between the different plants are large and the heat exchangers are often installed at different elevations within a plant. Pressure drop is mainly due to frictional losses as the fluids flow through pipes and fittings as well as pressure losses across the heat exchangers. When the fluids are liquid phase, there is additional pressure loss due to elevation changes. Failure to include the pressure drop factor in the early stages of design can lead to serious problems at the later stages. Exclusion of pressure drops when targeting minimum energy requirement (MER) may lead to too optimistic energy targets resulting in undersizing of central utilities systems. Neglecting pressure drops at the heat exchanger network (HEN) synthesis stage may render a proposed design infeasible if the actual pressure drops are higher than that what is allowable by the pumps or compressors. The need to replace the pumps or compressors may outweigh the savings from Heat Integration.

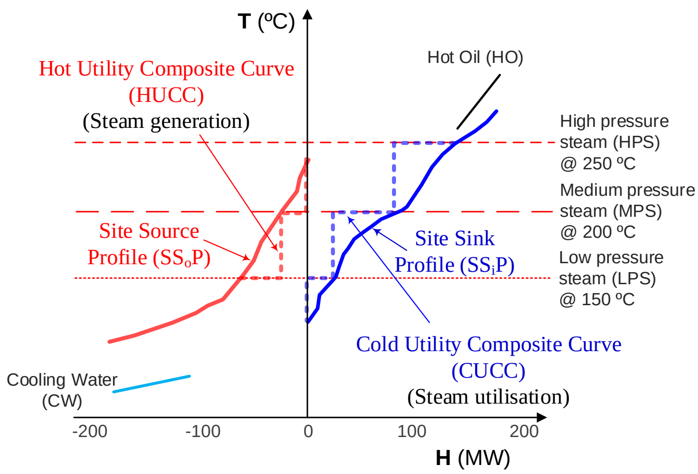
Most studies on pressure drop issues are associated with the retrofitting or synthesis of HEN for a single process. Mathematical Programming (MP)-based methodologies were mostly used to address the impact of pressure drop in the optimisation of HEN. Polley *et al*. [2] introduced the concept of pressure drop targeting in HEN retrofits where the pressure drop is correlated to the heat exchange area and heat transfer coefficient. The allowable pressure drop is used as an objective to optimise the heat exchange area. Ciric and Floudas [3] addressed the pressure drop issue based on the distances between heat exchangers and used a piping cost factor to minimise HEN modification costs. Ahmad and Hui [4] considered the pressure drop issue, in terms of distance between processes, by grouping the processes into “areas of integrity” and incorporated the impact in the methodology in the form of forbidden matches. Sorsak and Kranvanja [5] extended the Mixed Integer Non-linear Programming (MINLP) model of Yee and Grossman [6] to optimise the pressure drop and heat transfer coefficient. The pressure drop across the heat exchangers, both tube and shell sides, were estimated and considered in terms of pumping costs. Nie and Zhu [7] considered pressure drops in HEN retrofits by first estimating the pressure drop limits and then tackled the pressure drop constraints by optimising the area allocation, shell arrangement and use of heat transfer enhancement option. Panjeshahi and Tahouni [8] proposed a procedure whereby the pressure drop is considered together with the possibility of pump/compressor replacement when optimising area and utility costs. Soltani and Shafiei [9] introduced a new procedure which uses a genetic algorithm along with linear programming to retrofit HEN, including pressure drops. Stream pressure drop is correlated to area and heat transfer coefficient and the allowable pressure drops are introduced as constraints in the network optimisation.

Few studies have addressed pressure drops in the MER targeting stage. Zhu and Nie [10] considered the pressure drop aspect simultaneously with area and utility costs during the targeting and design stages. The pressure drop estimated for the heat exchanger is used to determine the optimum minimum approach temperature (ΔT_{min}) along with area and utility cost in the targeting stage. Inclusion of pressure drop (for heat exchangers only) in the proposed MP model led to different network structures and costs. Chew *et al.* [11] highlighted the significance of considering distribution piping pressure drop on steam generation from a Site Source. In the case study, the amount of steam recovered from the Site Source is significantly reduced when steam has to be generated at a higher pressure level to overcome the pressure drop in the pipes. Without considering pressure drops, the estimated utility targets maybe too optimistic and would result in undersizing of central steam generation systems. Liew *et al.* [12] extended the numerical algorithms, Total Site Problem Table Algorithm and Total Site Utility Distribution, to consider pressure drops and heat losses in steam pipes. The utility targets are based on a steam level which is at higher pressure (*i.e.*, to overcome the pressure drop) and superheated (*i.e.*, at a sufficient degree of superheat such that after heat loss the steam will reach the user at saturated conditions).

The studies so far have addressed the pressure drop factor in the optimisation of HEN in terms of pumping costs (based on distance or heat exchanger pressure drops), allowable pressure drop as constraints or objectives, or forbidden matches. The consideration of pressure drops in MER targeting has been at the heat exchanger (ΔT_{min}) or due to distance (steam pipes). None had looked at the pressure drop implications in a Total Site (TS) context which would encompass distance, equipment and utility distribution systems. Moreover, the MP-based methods provide few design insights required by designers [1]. In this paper, the graphical pinch-based TSHI methodology is extended to consider the pressure drop factor during the MER targeting stage. The methodology provides a more realistic estimation of MER targets and better understanding of the TSHI design for implementation later.

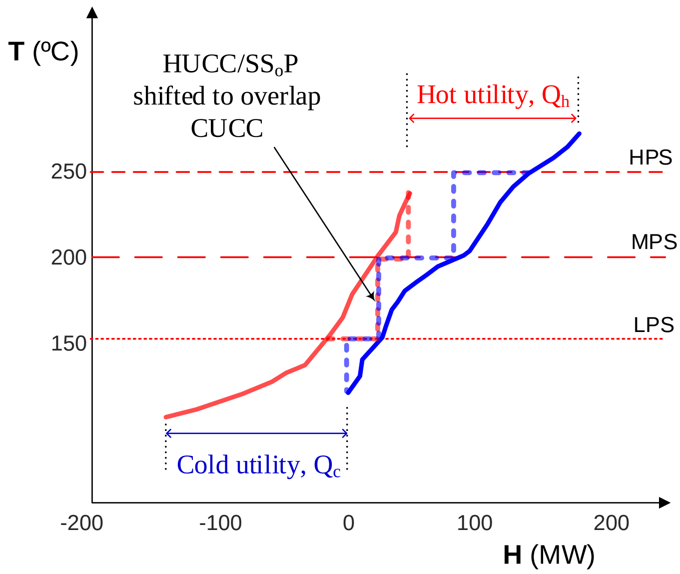
2. Pressure Drop Factor in TSHI

In the established TSHI methodology, the utility targeting are based on temperatures and heat loads. The overall heat surplus (Source) and deficit (Sink) of the processes in a TS are represented by the Total Site Profile (TSP). The potential utility generation from the source and heating requirement of the Sink are shown by the Site Utility Composite Curves (SUCC) which are then used to set the targets for site heating and cooling utilities requirements [13]. The steam utilities are generated (from Site Source) and utilised (at Site Sink) at the same temperatures, see Figure 1a,b.

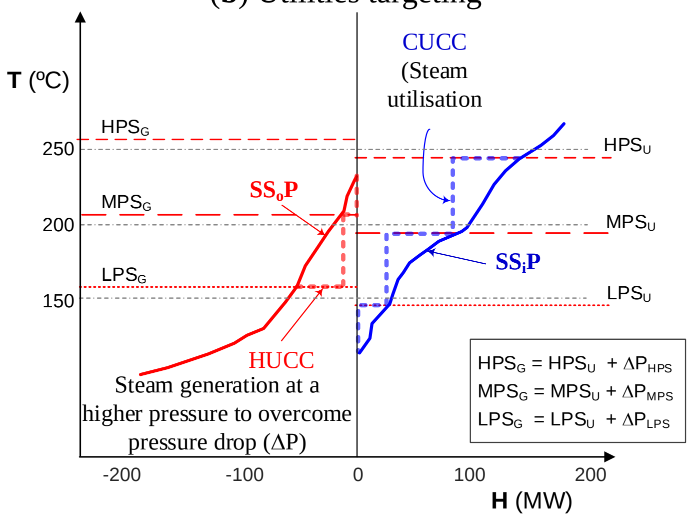


(**a**) TSP

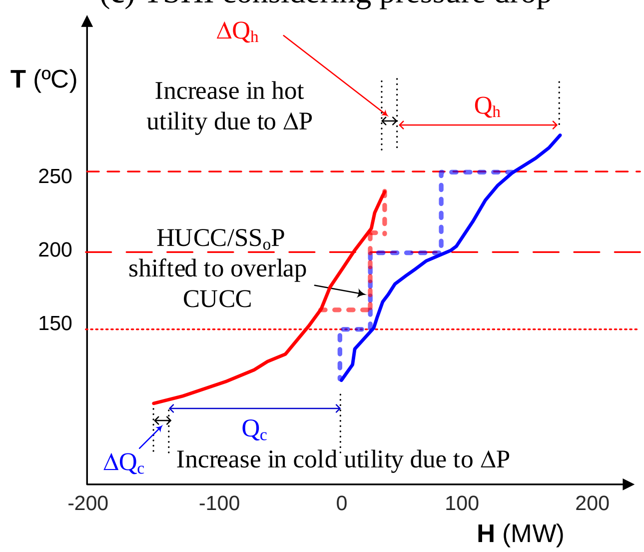
Figure 1. *Cont.*



(**b**) Utilities targeting



(**c**) TSHI considering pressure drop



(**d**) Utilities targeting considering pressure drop

Figure 1. TSHI utilities targeting (adapted from Klemeš *et al.* [13]).

In a TS, the utilities are distributed by an array of headers, sub-headers and pipes. Figure 2 gives a flow schematic of a TS comprising four plants with hot oil (HO), high pressure steam (HPS), medium pressure steam (MPS), low pressure steam (LPS) and cooling water (CW) utilities.

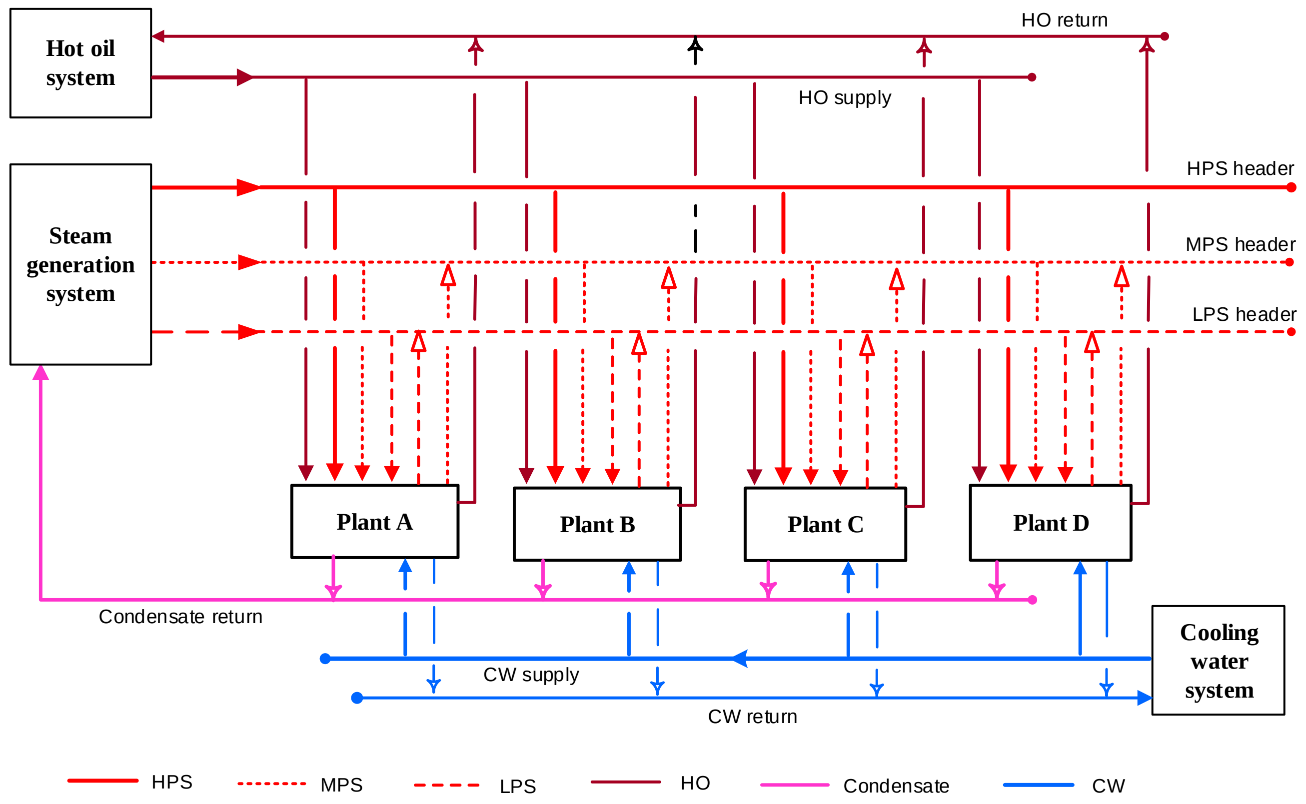


Figure 2. Schematic of a typical utilities distribution system at a TS with HO, HPS/MPS/LPS and cooling water.

2.1. Steams: HPS, MPS, LPS

The main headers take supply from the boilers and various steam generators which recover heat from the Site Source. Steam is then distributed to the various plants via sub-headers and distribution pipes. The main header operates at a sufficiently high pressure to supply steam to the furthest steam users. Figure 3 gives the process flow diagram of a typical steam generation and distribution system. Because of pressure drops in the headers, pipes and equipment, steam will be generated at a higher pressure and used at a lower pressure. The pressures and pressure drops of the steam distribution system are summarised in Figure 4. As saturated steam temperature is a function of its pressure, the difference in pressures between generation and usage can be represented by the difference in temperatures for generation and usage as shown in Figure 1c,d. As shown, consideration of the pressure drop factor will increase the heating (ΔQ_h) and cooling (ΔQ_c) utilities. In addition, the discharge head of the boiler feed water (BFW) pumps will have to be specified accordingly and the information used as input in the cost optimisation exercise.

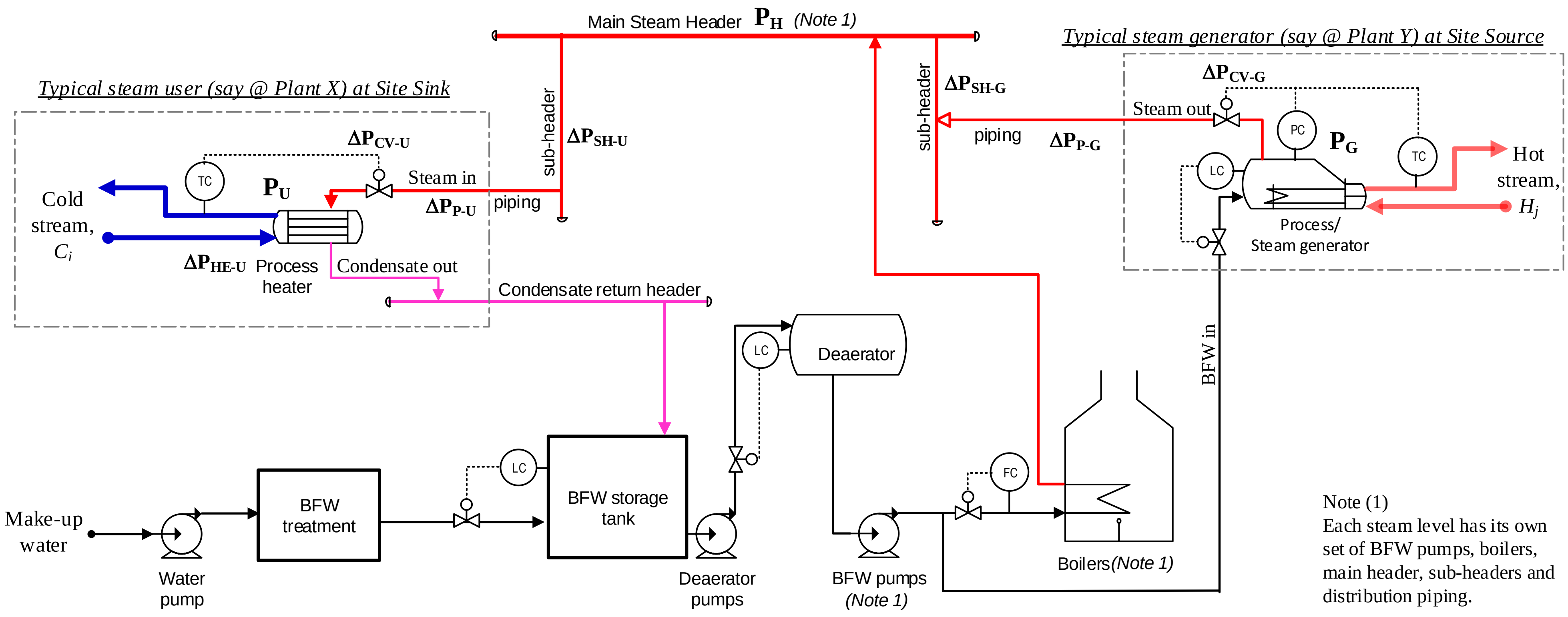


Figure 3. Process flow diagram—a typical steam generation, distribution and utilisation system at a TS.

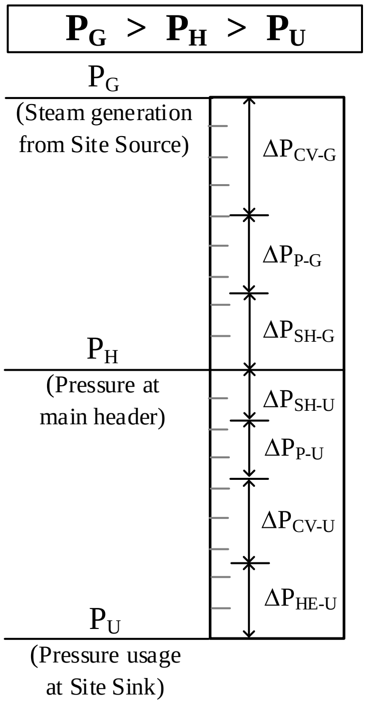


Figure 4. Pressures and pressure drops at a steam distribution system.

2.2. Cooling Water

Figure 5 is the flow diagram of a typical CW distribution system. The CW pumps deliver CW to the various users, *i.e.*, the process coolers, on the TS via the supply header, sub-headers and distribution piping. Warm CW exiting the coolers is routed to the cooling towers via the return header. For liquids like water, the temperature is not affected by its flow pressure. As long as there is no phase change, the pressure drop does not affect the MER targeting. However, the CW pumps have to be specified for a sufficient discharge head so as to overcome the pressure drop in the distribution system to ensure adequate volumes of the utility are delivered to the users as required. For liquid utilities such as CW, the elevation pressure drop due to liquid column static head (above the pump) is important and has to be considered. The required pump discharge head can then be used as an input parameter in the cost optimisation exercise.

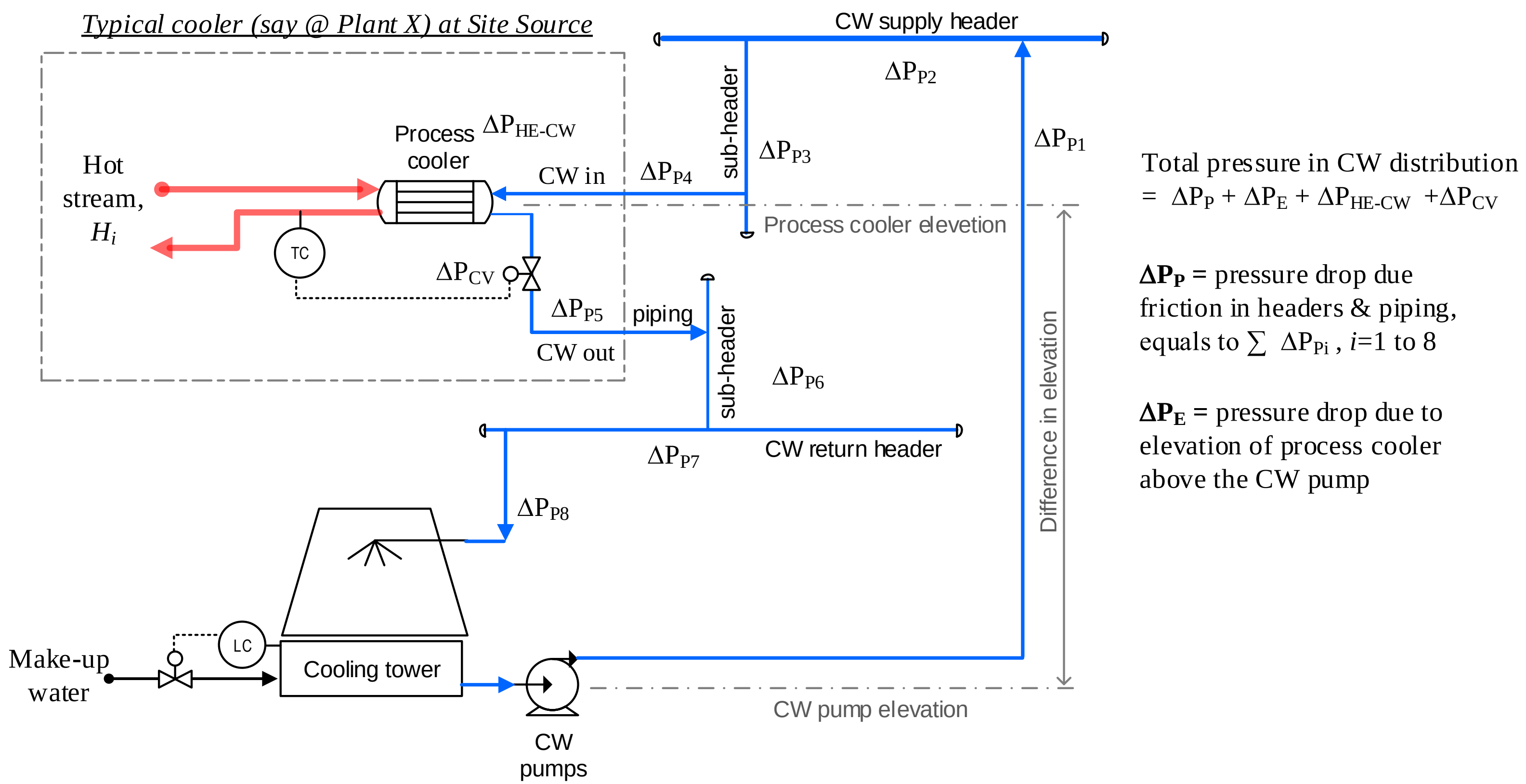


Figure 5. Process flow diagram—cooling water distribution system.

2.3. Hot Oil

Like CW, pressure drops do not affect MER targeting. Pressure drops due to elevation have to be included when estimating the discharge head for the HO circulation pumps and used as an input to the cost optimisation exercise. As with the liquid utilities, the impact of pressure drop on the process streams are seen in the penalty of additional pumping or compression costs so long as there is no phase changes, *i.e.*, liquid remains as liquid and gas stays as gas in the pipes. The impact of pressure drop on TSHI is summarised in Table 1.

Table 1. Impact of pressure drop on TS.

Fluid	MER Targeting	Cost Optimisation
Steam e.g., HPS, MPS, LPS	Increase ΔQ_h and ΔQ_c	Higher BFW pump capital and pumping costs
Liquid utilities (e.g., CW, HO, *etc.*)	No impact	Higher utility circulation pump capital and pumping costs
Process—liquids [(a)]	No impact	Higher pump capital and pumping costs
Process—gas [(b)]	No impact	Higher compressor capital and compressing costs

[(a)] Assume no phase change, liquid remains as liquid in the pipes; [(b)] assume no phase change, gas stays as gas in the pipes.

3. Pressure Drop Estimates

3.1. Steam Distribution System

Figure 3 is a process flow diagram of a steam generation and distribution system. The main steam header takes supply from the boilers and process/steam generators which recover heat from the Site Source. At the process/steam generator, a pressure control valve regulates the pressure at the heat exchanger ensuring that steam is generated at a sufficient pressure for delivery to the main header via the sub-header. The pressure drops between the process/steam generator and the main header, $\Delta P_{G\text{-}S}$:

$$\Delta P_{G-S} = \Delta P_{CV} + \Delta P_P + \Delta P_{SH} + \Delta P_H \quad (1)$$

The pressure drops between the process/steam user and the main header, $\Delta P_{S\text{-}U}$:

$$\Delta P_{S-U} = \Delta P_H + \Delta P_{SH} + \Delta P_P + \Delta P_{CV} + \Delta P_{HE} \quad (2)$$

where ΔP_{CV} is the pressure drop across the control valve, ΔP_{HE} is the pressure drop across the heat exchanger and ΔP_P, ΔP_{SH}, ΔP_H are the frictional pressure drops in the distribution pipe, sub-header and header.

The steam is assumed to be saturated and dry throughout the distribution network. Any condensate dropouts due to heat losses from the insulated pipe to the ambient and/or due to the Joule-Thompson effects of pressure drops are removed by steam traps located at strategic locations [14]. Heat loss from a steam distribution system occurs in several ways. In addition to the heat loss from the insulated pipes to the ambient a majority of the heat loss is through leaks in steam pipes, condensate return lines as well as steam traps. It is more appropriate to account for steam losses (which have to be made up by extra steam generation) as a percentage of steam consumption than to use a degree of superheating in the steam temperature as proposed by [12] to account for heat losses.

The frictional pressure drop in steam lines can be calculated using the Babcock equation [15]:

$$\Delta P_f = 2489 \{\frac{d + 3.6}{d^6}\} \frac{W^2 L}{\rho} \quad (3)$$

where W is the mass flow (kg/h), L is the pipe length (m), ρ is the single phase density (kg/m^3) and d is the pipe internal diameter (mm).

Alternatively, a steam line sizing nomograph, see Appendix 1, can be used for quick estimate of steam line pressure drops [14]. Commercial software such as Pipe module, which estimate pressure drop and heat loss in pipes, in the Aspen-HYSYS process simulator can also be used [16].

3.2. Cooling Water Distribution System

In Figure 5, pressure drop ΔP_{CW} at the CW distribution system, for a process/CW cooler, can be described as:

$$\Delta P_{CW} = \Delta P_{P} + \Delta P_{E} + \Delta P_{HE} + \Delta P_{CV} \quad (4)$$

where ΔP_P is the frictional pressure drop, ΔP_E is the elevation pressure drop, ΔP_{HE} and ΔP_{CV} are as described before. Equation (4) can generally be used for other liquid phase utilities such as HO, *etc.*

3.3. Frictional Pressure Drop in Liquid and Gas Lines, ΔP_P

Fluid flow always results in energy losses due to friction. The frictional losses will be have to be overcome by additional head required on the pump. The pressure drop due to friction can be estimated by the well-known Darcy-Weisbach equation [17]:

$$\Delta P_f = 0.5\, \rho\, f_m\, L\, V^2/d \quad (5)$$

where ρ is the density (kg/m^3), L is the length (m), V is the velocity (m/s) and d is the internal diameter of pipe (mm). f_m is the Moody friction factor, which depends on the Reynolds number (Re) and ε, the absolute roughness of the pipe for turbulent flow, typical of fluids flow in plant. Appendix 2 gives the values of ε and f_m for different pipe materials. These values are the iterative solution of the Colebrook correlation [17]:

$$\frac{1}{\sqrt{f_m}} = -2 \log_{10} \{\frac{\varepsilon}{3.7\, d} + \frac{2.51}{Re \sqrt{f_m}}\} \quad (6)$$

Equation (5) can be directly applied for liquid lines.

To estimate pressure drop in gas lines within plant or battery limits, the Darcy-Weisbach formula can be written in a simple form, assuming that the pressure drop through the line is less than 10% of the line pressure [17]. Pressure drop per 100 m of equivalent pipe length can be written as:

$$\Delta P_{100} = \frac{W^2}{\rho} \{\frac{62\,530\,(10^2) f}{d^5}\} \quad (7)$$

where W is the mass flow (kg/h), ρ is the single phase density (kg/m^3), f is the friction factor and d is the pipe internal diameter (mm).

3.4. Elevation Pressure Drop for Liquid Lines, ΔP_E

For liquid lines, the pressure drop due to static head of liquid column above the utility circulation pump need to be included. The elevation pressure drop has to be calculated separately using the following equation which is based on Bernoulli's Theorem:

$$\Delta P_E = 0.00981\, \rho_l\, Z_E \tag{8}$$

where ρ_l is the liquid density (kg/m^3) and Z_E is the elevation of the heat exchanger above the utility circulation pump centre line (m).

3.5. Pressure Drop across Heat Exchanger, ΔP_{HE}

During conceptual design, the type of heat exchanger or detailed geometry of the heat exchanger are often not available. Typical values of pressure drop based on company's guidelines or designer's experience can be used. Alternatively, the heat exchangers pressure drop can be estimated using established equations with some explicit assumptions on the heat exchanger geometries, for e.g., shell and tube heat exchangers: number of passes, tube diameter, tube length, tube pitch, tube configurations, baffle cuts, *etc.* [18].

3.6. Pressure Drop across Control Valve, ΔP_{CV}

The pressure drop across a control valve can be estimated if the characteristics of the control valve, C_v, is known. A larger pressure drop will increase pumping costs while a smaller pressure drop will increase valve costs. During the conceptual stage, when the details of the valves are not known, the usual rule of thumb is to use an allowable pressure drop of 10%–15% of total pressure drop, or 70 kPa, whichever is greater [19].

4. Methodology

The proposed methodology is presented in Figure 6 and described as follows.

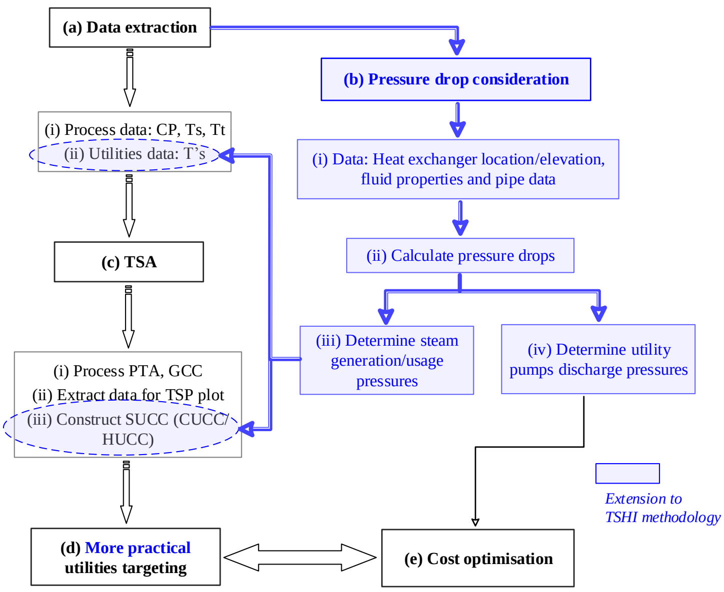


Figure 6. Algorithm to consider pressure drops in TSHI.

(a) Data extraction—extract stream and utilities data, *i.e.*, heat capacities (CP) and temperatures.

(b) To consider the pressure drop factor in TSHI:

(i) Information on the location of the heat exchangers, fluid properties and pipe data are required in order to estimate the pressure drops. Location and elevation of the heat exchangers can be obtained from the site plot plan, individual plant layout and elevation drawings. Fluid properties such as mass flow and density can be extracted from the heat and mass balances. Pipe data required are the internal diameter and roughness factor. For each plant on site, determine the header, sub-header and pipe lengths based on the process/utility heat exchangers located furthest from the reference point and the process/utility heat exchanger at the highest elevation.

(ii) The pressure drops can be estimated using the equations given in Section 3. Alternatively, pressure drops can be based on the typical ΔP per unit length for pipes, control valves and heat exchangers available from company guidelines or designer's experiences.

(iii) Determine steam generation/usage pressure and corresponding steam saturation temperatures. Referring to Figure 3 again, the steam usage pressure, P_U, is the steam pressure at the steam/process heater, furthest from the utility reference point:

$$P_{\mathrm{U}} = \Delta P_{\mathrm{S-U}} + P_{\mathrm{H}} \tag{9}$$

where, P_H is the header pressure.

The steam generation pressure, P_G, is the steam pressure at the process/steam generator furthest from the utility reference point

$$P_{\mathrm{G}} = P_{\mathrm{H}} + \Delta P_{\mathrm{G-S}} \tag{10}$$

The steam saturation temperatures at P_U and P_G can be obtained from the steam tables.

(iv) Determine utility pumps discharge pressure.

Referring to Figure 5, the CW pump discharge pressure reads as:

$$P_{\mathrm{PUMP}} = P_{\mathrm{DES}} + \Delta P_{\mathrm{CW}} \tag{11}$$

where subscript DES denotes destination, at the process/CW cooler furthest from the CW pumps.

(c) Carry out TS analysis:

(i) Prepare the TSP from individual process PTA and GCC [13]. The utility usage and generation are directly interpolated on the TS-PTA at the respective utilities temperatures [20]. An example of the TS-PTA is given in Table 3.

(ii) A graphical representation of the SUCC can be obtained from the TS-PTA, see Figure 8.

(d) Utilities targeting—Steam is generated and used at different temperatures due to the pressure drops in the steam distribution network. The TS energy targets are determined using the pinch-based graphical and algebraic method [20].

(e) Pressure drops determined for liquid utility systems can be used as an input to the cost optimisation in terms of higher pumping cost and the constraints in allowable ΔP.

5. Illustrative Examples

The TS consists of four plants A, B, C and D with hot oil (HO), HPS, MPS, LPS and cooling water (CW) utility systems as depicted in Figure 2. A simplified plot plan and elevation drawing is given in Figure 7.

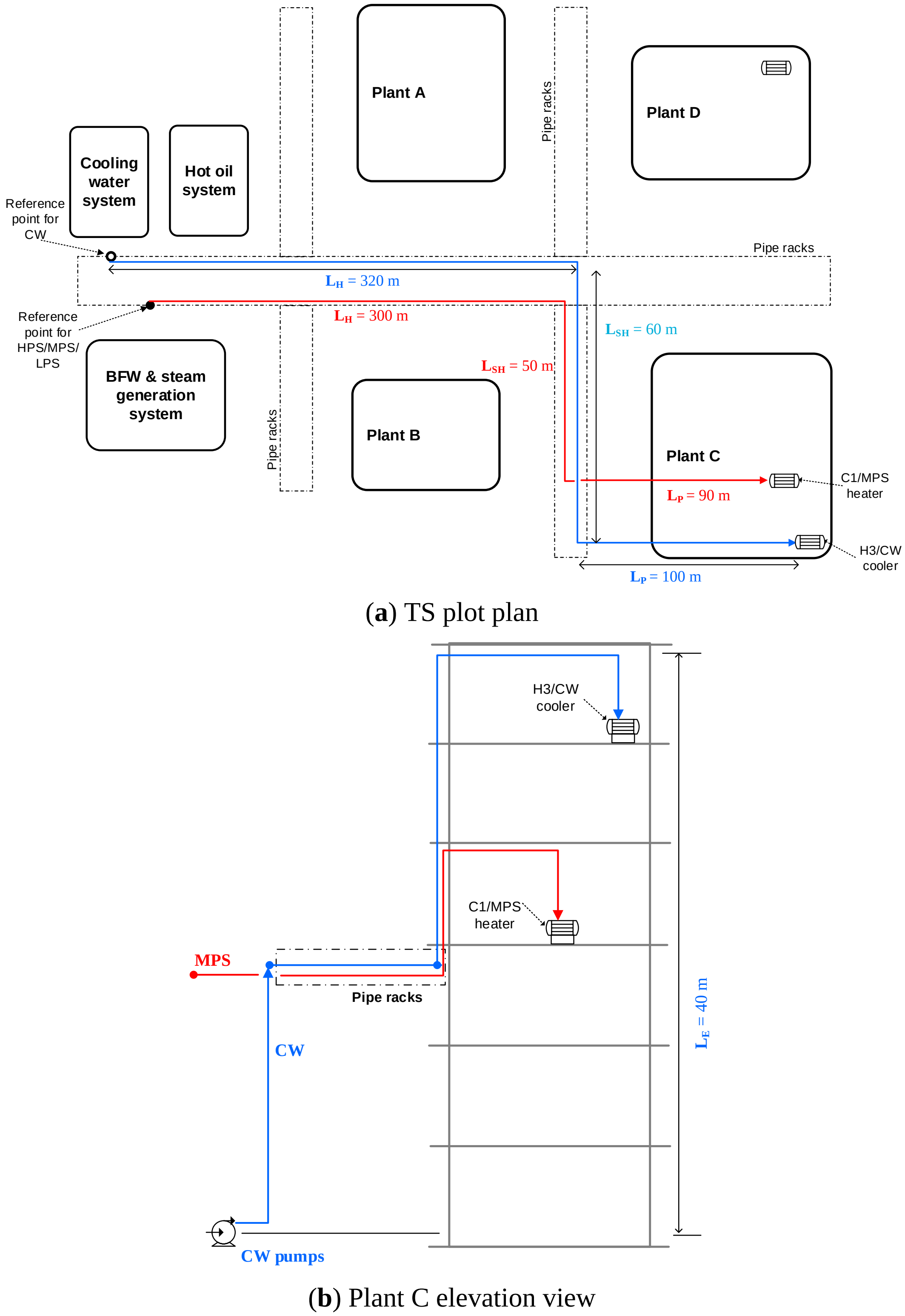


Figure 7. Simplified plot plan and elevation drawing for the TS.

For LPS, $P_{U\text{-}LPS}$ is governed by stream C1/LPS heater at Plant D, located furthest from the main LPS header, while $P_{G\text{-}LPS}$ is governed by stream H1/LPS steam generator at the same Plant D. For MPS, $P_{U\text{-}MPS}$ is governed by stream C1/MPS heater at Plant C located furthest from the main MPS header while $P_{G\text{-}MPS}$ is governed by stream H1/MPS steam generator at the same Plant C. For HPS, $P_{U\text{-}HPS}$ is governed by stream C1/HPS heater at Plant C, located furthest from the main HPS header. There is no HPS steam generation on site.

A summary of the stream data, layout and elevation information for the estimation of pressure drops is given in Table 2. Figure 8 shows the TSP and SUCC of the TS. The results of the pressure drops estimation and the corresponding steam generation and usage temperatures for the steams and CW distribution networks are summarised in Table 3. Table 4 gives the modified TS-PTA by which the utilities usage and generation are interpolated from the Site Sink and Site Source PTA. The revised SUCC, with consideration for pressure drops, are superimposed on Figure 8.

Table 2. Summary of input data for TS analysis.

Process	Stream	CP (MW/°C)	T_s (°C)	T_t (°C)	Length, *L*/Elevation, E [(1)]				
					L_H (m)	L_{SH} (m)	L_P (m)	E (m)	Heat exch. Furthest from Utility Reference Point
A	H1	0.35	260	225					
	H2	1.15	260	195					
	H3	0.50	195	130					
	C1	1.25	240	255					
	C2	0.65	175	260					
	C3	0.20	155	205					
B	H1	0.36	260	175					
	H2	0.60	260	115					
	H3	0.75	175	95					
	C1	1.10	175	255					
	C2	0.20	110	175					
	C3	0.89	95	155					
C	H1	0.62	225	155	300	50	90		H1/MPS
	H2	0.32	195	95					
	H3	1.00	130	85	320	60	100	40	H3/CW
	C1	0.60	110	240	300	50	85		C1/HPS, C1/MPS
	C2	0.40	155	240					
	C3	0.70	110	175					
D	H1	0.41	130	85	300	50	90		H1/LPS
	H2	0.10	110	80					
	H3	0.15	95	70					
	C1	0.20	90	140	300	50	80		C1/LPS
	C2	0.50	60	110					
	C3	0.40	50	100					
Utility	**T_s (°C)**		**T_r (°C)**						
HO	300		260		$\Delta T_{min\text{-}pp}$ is			20	°C
HPS	250		-		$\Delta T_{min\text{-}pu}$ is			15	°C
MPS	200		-						
LPS	150		-						
CW	25		45						

[(1)] Piping lengths are only extracted for those heat exchangers furthest from the utilities reference point, *i.e.*, which govern the steam generation and usage levels and utility circulation pump sizing. Only steam and CW are considered.

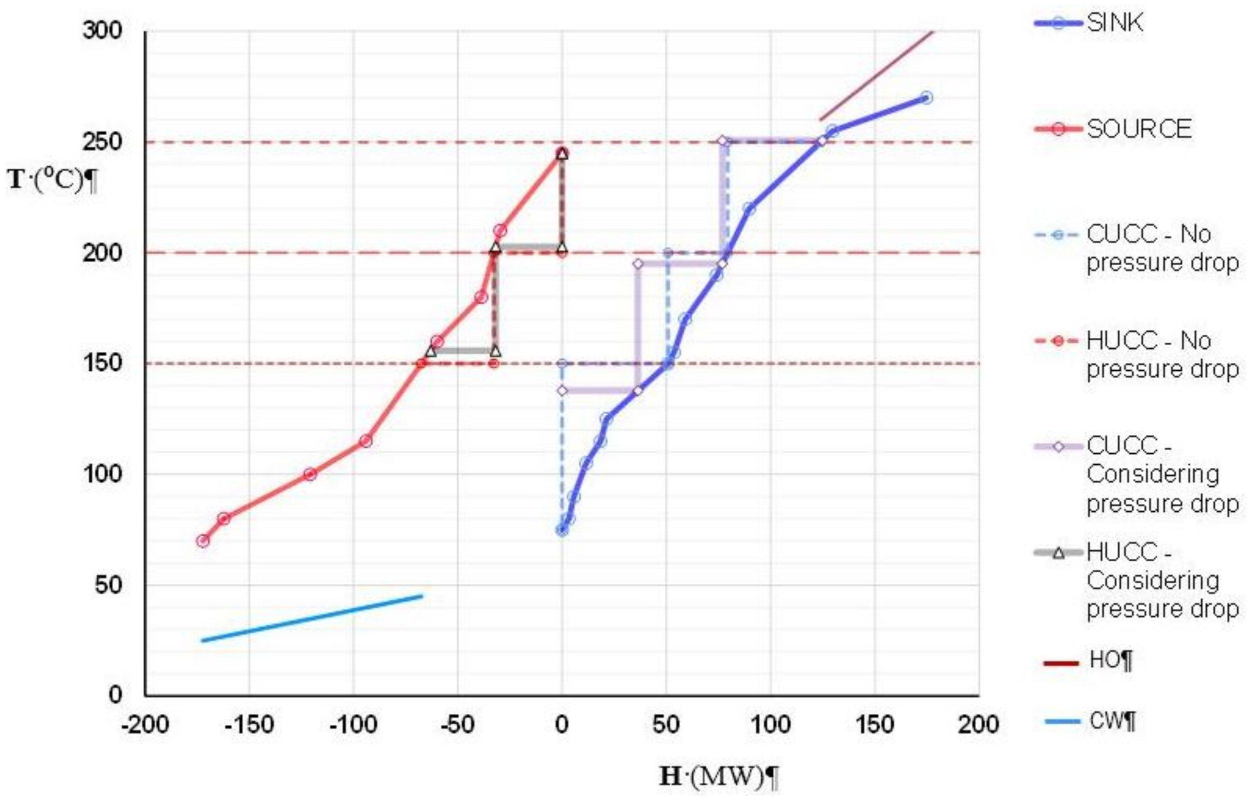


Figure 8. Simplified plot plan and elevation drawing for the TS.

Due to pressure drops in the headers, sub-headers, piping and across control valves and heat exchangers, steams have to be generated at a higher value than their usage. A comparison of utility targeting with and without consideration of pressure drop is given in Table 5. The impact of pressure drop is more notable for steam at low pressure, due to its higher volumetric flow. From Table 3, the differences in steam usage and generation temperatures are 18.1 ℃ and 7.7 ℃ for LPS and MPS. From Table 5, the overall heating utilities increases by 14.7 MW (14.5%) and the cooling utility increases by 4.7 MW or (4.5%) when pressure drop is taken into consideration. The HPS requirement increases by 3.4 MW, the MPS usage increases by 11.9 MW while LPS usage reduces by 14.4 MW. Excluding pressure drop could lead to over estimation of the amount of steam that can be raised at the Site Source for HPS and MPS leading to the undersizing of central HPS and MPS generation capacities.

Table 3. Summary of pressure drops estimation for steam and CW distribution networks.

Operating parameter			LPS Usage	LPS Generation	MPS Usage	MPS Generation	HPS Usage	CW
Header pressure		kPag	375	375	1453	1453	3831	-
Header temp.		℃	150	150	200	200	250	-
Pressure drops [(1)]:	ΔP_{H}	kPa	33	33	33	33	33	-
	ΔP_{SH}	kPa	5.5	5.5	5.5	5.5	5.5	-
	ΔP_{P}	kPa	10.8	9.6	9	9.6	9	-
	ΔP_{CV}	kPa	35	35	50	50	50	70
	ΔP_{HE}	kPa	50	-	50	-	50	100
	ΔP_{f}	kPa	-	-	-	-	-	218 [(2)]
	ΔP_{E}	kPa	-	-	-	-	-	392.4
Total pressure drops		kPa	134	83.1	148	98.1	148	780.4
Pressure @ user	P_{U}	kPag	240.7	-	1305.5	-	3683.5	
Temperature @ user	T_{U}	℃	137.8	-	195.1	-	247	
Pressure @ generation	P_{G}	kPag	-	458.1	-	1551	-	
Temperature @ generation	T_{G}	℃	-	155.9	-	202.8	-	
ΔT between usage and generation		℃	18.1		7.7			
Pressure @ CW pump		kPag						980.4 [(3)]

[(1)] A frictional pressure drop of 0.11 kPa/m has been assumed for the headers and sub-headers and 0.12 kPa/m for the piping; [(2)] Total frictional pressure drops at supply/return headers, sub-headers and piping; [(3)] Based a destination pressure, *i.e.*, pressure at the H3/CW cooler within Process C, of 200 kPag.

Table 4. TS-PTA for Site Source and Site Sink with utilities usage and generation.

(a) Site Sink PTA

T** **(°C)**	**Δ*T* (°C)**	**Process CP**				**Σ CP (MW/°C)**	**Δ*H* (MW)**	**Cascade *H* (MW)**	***H*** [(1)] **(MW)**	**Utility Usage**
		A (MW/°C)	**B (MW/°C)**	**C (MW/°C)**	**D (MW/°C)**					***H* (MW)**
75						0	0	0		
80	5				0.65	0.65	3.3	3.3		
90	10				0.24	0.24	2.4	5.7		
105	15				0.39	0.39	5.9	11.5		
115	10				0.69	0.69	6.9	18.4		
125	10				0.29	0.29	2.9	21.3		
137.8									36.4	LPS = 36.4
150	25			0.98	0.20	1.18	29.5	50.8		
155	5			0.36	0.20	0.56	2.8	53.9		
170	15			0.36		0.36	5.4	59.0		
190	20			0.76		0.76	15.2	74.2		
195.1									76.9	MPS = (76.9 − 36.4) = 40.5
220	30		0.14	0.38		0.52	15.6	89.8		
250.7									124.8	HPS = (124.8 − 76.9) = 47.9
255	35		0.14	1.00		1.14	39.9	129.7		
270	15	1.90	1.10			3.00	45.0	174.7		
275	5	0.65				0.65	3.3	178.0		

(1) Interpolate at the steam temperatures.

Table 4. *Cont.*

(b) Site Source PTA

*T*** (°C)	Δ*T* (°C)	Process CP				Σ CP (MW/°C)	ΔH (MW)	Cascade *H* (MW)	*H* (1) (MW)	Utility Usage
		A (MW/°C)	B (MW/°C)	C (MW/°C)	D (MW/°C)					*H* (MW)
245						0	0	0		
210	35	0.85				0.85	29.8	29.8		
202.8									31.9	MPS = 31.9
180	30	0.30				0.30	9.0	38.8		
160	20	0.30	0.76			1.06	21.2	60.0		
155.9									63.1	LPS = (63.1 − 31.9) =31.2
115	45	0.50	0.26			0.76	34.2	94.2		
100	15		0.46	1.32		1.78	26.7	120.9		
80	20		0.75	1.32		2.07	41.4	162.3		
70	10			1.00		1.00	10.0	172.3		

T* Double shifted temperature for TSP plot and TS-PTA, °C; (1) Interpolate at the steam temperatures.

Table 5. Impact of pressure drop on TS.

Utilities	Base Case (No Pressure Drops)			Case 1 (with Pressure Drops)			(Case 1)—(Base Case)		
	Usage (MW)	Generation (MW)	Nett (MW)	Usage (MW)	Generation (MW)	Nett (MW)	Usage (MW)	Generation (MW)	Nett (MW)
HO	54.0	-	54.0	53.2	-	53.2	−0.8	-	−0.8
HPS	44.6	-	44.6	48.0	-	48.0	+3.4	-	+3.4
MPS	28.6	32.8	−4.2 (1)	40.5	31.9	8.6	+11.9	−0.9	+8.6
LPS	50.8	34.8	11.8 (1)	36.4	31.2	5.2	−14.4	−3.8	−6.8
Total heating			100.4			115.0			+14.6
CW	-	-	104.7			109.2			+4.7

(1) Excess MPS generated is used for LPS heating. Nett LPS heating is (50.8 − 34.8 − 4.2) = 11.8 MW.

The pressure drop in liquid utilities does not affect TSHI MER targeting, however it should be considered and used as an input parameter when evaluating the TSHI options for economic evaluation. Exclusion of pressure drops will lead to undersizing of pumps or compressors leading to infeasible design solutions, and expensive re-design at the detailed design stage.

6. Conclusions

A systematic methodology that considers pressure drops in TSHI utility targeting has been developed. The case study proved that ignoring pressure drops in TSHI design led to optimistic MER targets and resulted in undersizing of external steam generation capacity. While pressure drops of liquid utilities such as water do not affect MER targeting, the pressure drop information should be incorporated in the economic evaluation of TSHI options. Pressure drops due to pipe friction, elevation changes and pressure drops across control valve and heat exchangers all need to be accounted for. Incorporation of pressure drops leads to closer to real life MER targeting and design. The proposed methodology can benefit from the visualisation advantages of the graphical method and from the precision of the numerical method and should be of the benefit to both industry and academia [21].

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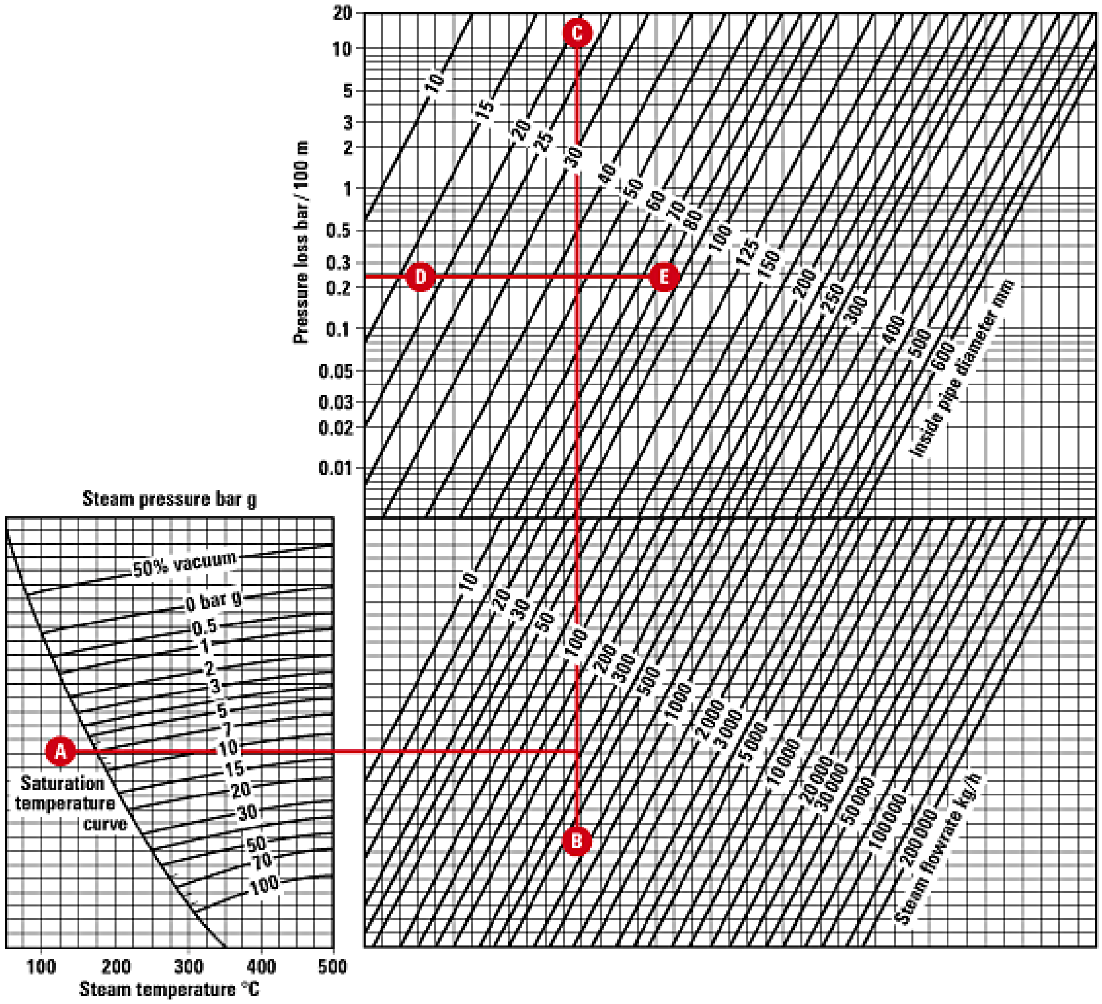
Author Contributions

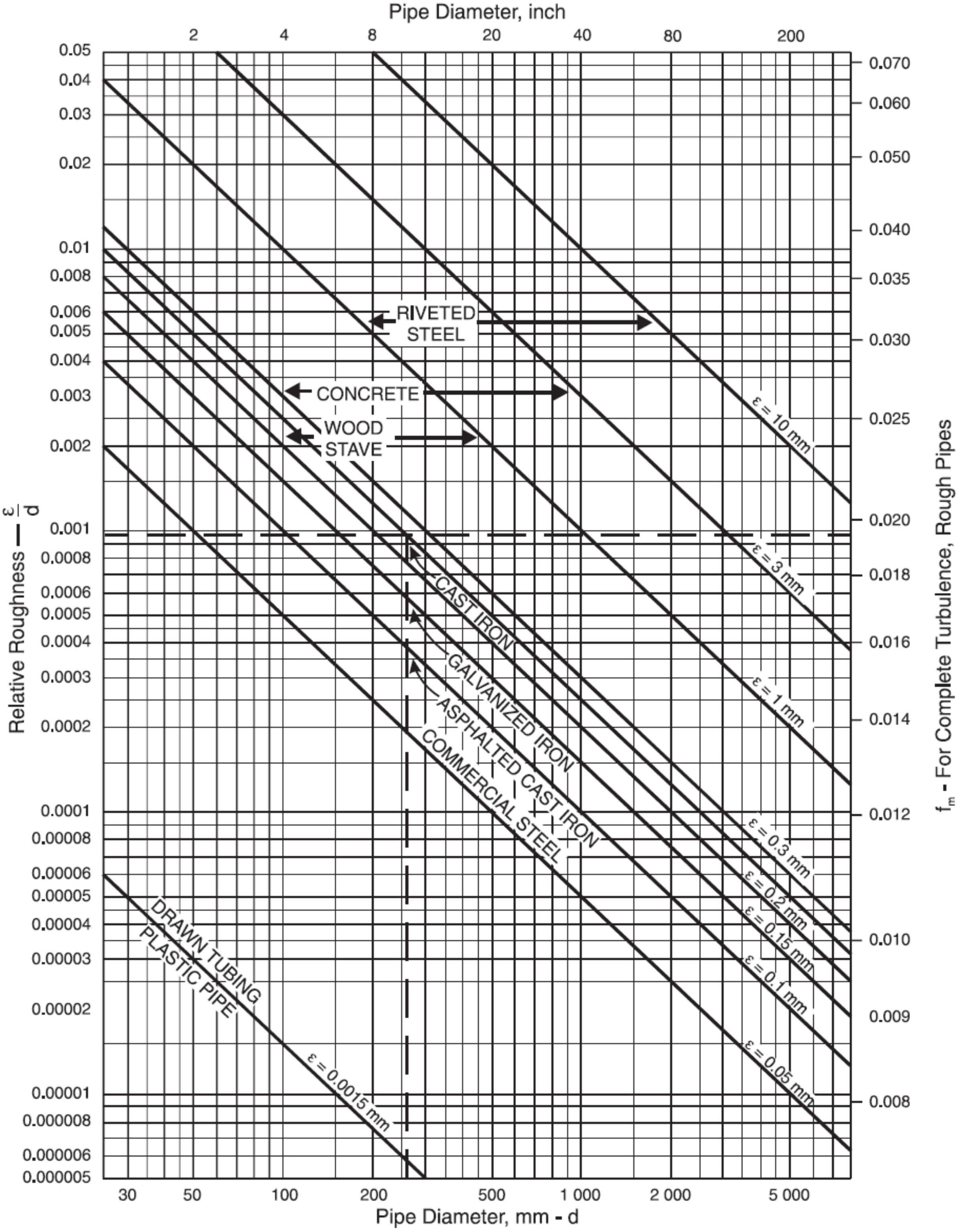
Jiří Jaromír Klemeš, Sharifah Rafidah Wan Alwi, Zainuddin Abdul Manan and Andrea Pietro Reverberi conceived the idea of research, provide guidance and supervision; Kew Hong Chew implemented the research, performed the analysis and wrote the paper. All authors have contributed significantly to this work.

Appendix 1. Steam Line Sizing Chart—Pressure Drop (Spirax Sarco, 2014).



- Select the steam pressure at the saturated steam line (7 barg), A;
- From A, draw a horizontal line to the steam flowrate (286 kg/h) and mark B;
- From B, draw a vertical line to the top of nomograph, C;
- Draw a horizontal line from 0.24 bar/100 m (allowable DP) on the pressure loss scale (DE);
- Point which BC crosses DE will indicate the pipe size required.

Appendix 2. Relative Roughness of Pipe Materials and Friction Factors for Complete Turbulence (GPSA, 1998).



Abbreviations

BFW	Boiler feed water
CUCC	Cold Utility Composite Curve
CV	Control valve
CW	Cooling water
FC	Flow control
GCC	Grand Composite Curve
HE	Heat exchanger
HEN	Heat exchanger network
HI	Heat Integration
HO	Hot oil
HPS	High pressure steam
HUCC	Hot Utility Composite Curve
LC	Level control
LPS	Low pressure steam
MINLP	Mixed integer non-linear programming
MP	Mathematical Programming
MPS	Medium pressure steam
MER	Minimum energy requirement
PC	Pressure control
PTA	Problem Table Analysis
SUCC	Site utility Composite Curves
SS_iP	Site Sink Profile
SS_oP	Site Source Profile
TC	Temperature control
TS	Total Site
TS-PTA	Total Site Problem Table Analysis
TSHI	Total Site Heat Integration
TSP	Total Site Profile
VHPS	Very high pressure steam

Nomenclature

CP	Heat capacity flowrate, MW/ ℃
d	Pipe internal diameter, mm
ε	Pipe roughness factor, m
Q_c	Cooling utilities heat flowrate, MW
Q_h	Heating utilities heat flowrate, MW
H	Process heat flowrate, MW
ΔP	Pressure drop, kPa
ΔT_{min}	Minimum approach temperature, ℃

$\Delta T_{min\text{-}pp}$	Minimum approach temperature between process and process, ℃
$\Delta T_{min\text{-}pu}$	Minimum approach temperature between process and utility, ℃
f_m	Moody friction factor
L	Length, m
P	Pressure, kPag
Re	Reynolds number
ρ	Density, kg/m^3
T	Temperature, ℃
T^*	Shifted temperature for process PTA, ℃
T^{**}	Double shifted temperature for TSP plot and TS-PTA, ℃
V	Velocity, m/s
W	Mass flow, kg/h
Z	Elevation, m

Subscripts

CV	Control valve
CW	Cooling water
DES	Destination
E	Elevation
f	Friction
G	Generation
H	Header
HE	Heat exchanger
l	Liquids
P	Piping
r	Return
S	Steam
s	Supply
SH	Sub-header
t	Target
U	Utilisation

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Klemeš, J.J.; Varbanov, P.S.; Kravanja, Z. Recent developments in process integration. *Chem. Eng. Res. Des.* **2013**, *91*, 2037–2053.
2. Polley, G.T.; Panjehshahi, M.H.; Jegede, F.O. Pressure drop considerations in the retrofit of heat exchanger networks. *Chem. Eng. Res. Des.* **1990**, *68*, 211–220.

3. Ciric, A.M.; Floudas, C.A. A mixed integer nonlinear programming model for retrofitting heat-exchanger networks. *Ind. Eng. Chem. Res.* **1990**, *29*, 239–251.
4. Hui, C.W.; Ahmad, S. Minimum cost heat recovery between separate plant regions. *Comput. Chem. Eng.* **1994**, *18*, 711–728.
5. Sorsak, A.; Kranvanja, Z. Simultaneous MINLP synthesis of heat and power integrated heat exchanger network. *Comput. Chem. Eng. Suppl.* **1999**, S143–S147.
6. Yee, T.F.; Grossman, I.E. Simultaneous optimisation models for heat integration—II. Heat exchanger network synthesis. *Comput. Chem. Eng.* **1990**, *14*, 1165–1184.
7. Nie, X.R.; Zhu, X.X. Heat exchanger network retrofit considering pressure drop and heat transfer enhancement. *AIChE J.* **1999**, *45*, 1239–1254.
8. Panjaeshahi, M.H.; Tahouni, N. Pressure optimisation in debottlenecking of heat exchanger networks. *Energy* **2008**, *33*, 942–951.
9. Soltani, H.; Shafiei, S. Heat exchanger networks retrofit with considering pressure drop by coupling genetic algorithm with LP (linear programming) and ILP (integer linear programming) methods. *Energy* **2011**, *36*, 2381–2391.
10. Zhu, X.X.; Nie, X.R. Pressure drop considerations for heat exchanger network grassroots design. *Comput. Chem. Eng.* **2002**, *26*, 1661–1676.
11. Chew, K.H.; Klemeš, J.J.; Wan Alwi, S.R.; Abdul Manan, Z. Industrial implementation issues of Total Site Heat Integration. *Appl. Therm. Eng.* **2013**, *61*, 17–25.
12. Liew, P.Y.; Wan Alwi, S.R.; Klemeš, J.J. Total Site Heat Integration targeting algorithm incorporating plant layout issues. *Comput. Aided Chem. Eng.* **2014**, *33*, 1801–1806.
13. Klemeš, J.J.; Dhole, V.R.; Raissi, K.; Perry, S.J.; Puigjaner, L. Targeting and design methodology for reduction of fuel, power and CO_2 on total sites. *Appl. Therm. Eng.* **1997**, *17*, 993–1003.
14. Spirax Sarco, Resources. Available online: spiraxsarco.com/resources/steam-engineering-tutorials/steam-distribution/pipes-and-pipe-sizing.asp (accessed on 23 September 2014).
15. *Flow of Fluids through Valves, Fittings and Pipe*; Technical Paper No. 410; Crane Co.: Chicago, IL, USA, 1988.
16. Aspen-HYSYS (Version 2006) (computer software). AspenTech: Burlington, MA, USA, 2014.
17. Gas Processing Supplier Association (GPSA). Fluid flow and piping. In *GPSA Engineering Data Book*, 11th ed.; GPSA: Tulsa, OK, USA, 1998; Volume 17, pp. 1–28.
18. Smith, R. *Chemical Process—Design and Integration*; McGraw-Hill: New York, NY, USA, 2005.
19. Choudhury, A.A.S.; Nwaoha, C.; Vishwasrao, S.V. In *Process Plant Equipment: Operation, Control and Reliability*; Holloway, M.D., Nwaoha, C.N., Onyewuenyi, O.A., Eds.; Wiley: New York, NY, USA, 2012; pp. 9–15.
20. Chew, K.H.; Klemeš, J.J.; Wan Alwi, S.R.; Manan, Z.A. Process Modifications to Maximise Energy Savings in Total Site Heat Integration. *Appl. Therm. Eng.* **2014**, doi:10.1016/j.applthermaleng.2014.04.044.
21. Klemeš, J.J. Industry-academia partnership. *Clean Technol. Environ. Policy* **2013**, *15*, 861–862.