IMPROVED TOTAL SITE HEAT INTEGRATION INCORPORATING PRESSURE DROP AND PROCESS MODIFICATIONS

CHEW KEW HONG

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Chemical Engineering)

Faculty of Chemical Engineering
Universiti Teknologi Malaysia

APRIL 2015

Dedicated specially to my parents, family and friends…

ACKNOWLEDGEMENT

At the close of this research work, I would like to express my heartfelt gratitude to those individuals who have got me to where I am today. This thesis though written by myself would not be possible without the support and input of my main supervisor Assoc. Prof. Ir. Dr. Sharifah Rafidah Wan Alwi, my co-supervisors Prof. Dr. Jiří Jaromír Klemeš and Prof. Dr. Zainuddin Abdul Manan. There have been many stimulating discussions, patient and constructive comments as well as valuable advices over the past three years which have generated the key ideas for the research and enabled the completion of the subsequent works.

I would like to extend my appreciation to my fellow post-graduate students in the Process Systems Engineering Centre (PROSPECT) who have helped me in one or another, and made my stay in this research group a meaningful and pleasant one.

A special thank goes to my family and friends who have always been an encouragement to me throughout the three years.

Above all, I would like to thank God for giving me the opportunity to do the research at Universiti Teknologi Malaysia and the ability to complete this research.

ABSTRACT

Heat Integration (HI) has been a well-established energy conservation strategy in the industry. Total Site Heat Integration (TSHI) has received growing interest since its inception in the 90's due to the ample energy saving potential available from TSHI implementation. This study assesses the TSHI methodology for industrial implementation and extended the TSHI methodology to (a) incorporate pressure drop, (b) maximise energy saving and (c) reduce capital cost of heat transfer area. A detailed assessment of the current TSHI methodology for industrial implementation has identified five key issues influencing the TSHI solution: (1) design, (2) operations, (3) reliability/availability/maintenance (RAM), (4) regulatory/policy and (5) economics. By considering these issues in the early stages, practical TSHI solutions can be obtained. This assessment has provided a direction for future extension of TSHI methodology from the industrial perspective. This work has also extended the TSHI methodology to consider pressure drop, one of the key design issues for Total Site (TS) due to large distances between plants. Pressure drop reduces the amount of steam that can be raised from the Site Source and changes the profile of hot utilities at the various levels. The utility circulation pumps have to be designed for a higher discharge head to overcome the frictional and elevation head loss in the distribution network. Consideration of pressure drop leads to an increase of about 4 % to both the heating and cooling utility requirements and significantly change the hot utilities profile between -75 % and +54 %. The improved methodology provides a more realistic basis for the design of central utility systems and the utility circulation pumps. The second and third extended TSHI methodologies complement the individual process analysis by bringing it within the TS context. The second methodology adapts the Plus-Minus Principle and applied it to TS. It identifies the options to maximise energy savings on site using the Total Site Profiles (TSP), the Utility Grand Composite Curve and a new set of heuristics. With the proposed process modifications, a case study performed demonstrated that a potential saving of 9 % in overall heating and 7 % in cooling utilities can be achieved. The third methodology adapts the Keep-Hot-Stream-Hot and Keep-Cold-Stream-Cold Principles to TS. Together with the TSP, the expanded TS Problem-Table-Algorithm and a comprehensive set of heuristics, the TSP is favourably changed to provide a larger temperature driving force to reduce the capital cost of the heat transfer units. The proposed modifications resulted in a modest reduction of heating and cooling utilities of between 1 % and 4 %, respectively and a more noticeable capital cost saving of about 9 %. These two methodologies enable the plant designers/engineers to pinpoint process modification efforts to improve site HI. The proposed changes to the process/streams should be assessed from feasibility, practicality and economic perspectives.

ABSTRAK

Integrasi Haba (HI) adalah merupakan salah satu strategi pemuliharaan tenaga yang mantap di dalam industri. Integrasi Haba Keseluruhan Tapak (TSHI) telah menerima minat yang semakin meningkat sejak kaedah ini dicipta pada tahun 90’an atas sebab potensi penjimatan tenaga yang tinggi yang boleh direalisasikan daripada perlaksanaan TSHI. Kajian ini menaksir metodologi TSHI di dalam pelaksanaan industri dan mengembangkan metodologi berkenaan untuk (a) mengambil kira kejatuhan tekanan, (b) memaksimumkan penjimatan tenaga dan (c) mengurangkan kos modal kawasan pemindahan haba (HTA). Penilaian terperinci terhadap metodologi TSHI bagi pelaksanaan industri telah mengenal pasti lima isu-isu utama yang mempengaruhi penyelesaian TSHI: (1) reka bentuk, (2) operasi, (3) kebolehpercayaan/ketersediaan/penyenggaraan, (4) peraturan/dasar dan (5) ekonomi. Dengan mempertimbangkan isu-isu ini di peringkat awal, penyelesaian TSHI lebih dekat kepada kehidupan sebenar boleh diperolehi untuk pelaksanaan. Penilaian ini telah menyediakan hala tuju masa depan untuk pengembangan metodologi TSHI dari perspektif industri. Metodologi TSHI diperluaskan untuk mengambil kira kejatuhan tekanan, salah satu isu yang penting untuk Keseluruhan Tapak (TS) kerana jarak yang jauh antara loji-loji. Kejatuhan tekanan mengurangkan jumlah stim yang boleh dijanakan daripada Sumber Tapak dan menukar profil utiliti panas di pelbagai peringkat. Pam peredaran utiliti perlu direka untuk turus pelepasan yang lebih tinggi untuk mengatasi kehilangan geseran dan ketinggian dalam rangkaian pengedaran. Kejatuhan tekanan meningkatkan kira-kira 4 % kedua-dua keperluan utiliti panas dan sejuk dan mengubahkan profil utiliti panas dengan ketara di antara -75 % kepada +54 %. Metodologi yang lebih baik ini memberi asas yang lebih realistik untuk mereka bentuk sistem utiliti pusat dan pam peredaran utiliti. Pengembangan Metodologi TSHI yang kedua dan ketiga melengkapkan analisis proses individu dengan mengaplikasikan prinsip berkenaan di dalam konteks TS. Metodologi yang kedua menyesuaikan Prinsip Campur-Tolak untuk TS. Metodologi ini mengenal pasti pilihan untuk memaksimumkan penjimatan tenaga di tapak dengan menggunakan TSP, lengkungan Utiliti Besar Komposit dan satu set baru heuristik. Dengan pengubahsuaian yang dicadangkan, potensi penjimatan 9% dan 7% dalam utiliti panas dan sejuk boleh dicapai. Metodologi yang ketiga menyesuaikan Prinsip Kekalkan-Panas-Aliran-Panas dan Kekalkan-Sejuk-Aliran-Sejuk untuk TS. Bersama dengan TSP, TS-Masalah-Jadual-Algoritma berkembang dan satu set komprehensif heuristik, TSP boleh diubahsuaikan untuk memberikan suhu penggerak yang lebih besar untuk mengurangkan HTA dalam TSHI. Ubah suaian yang dicadangkan menghasilkan pengurangan sederhana utiliti panas dan sejuk masing-masing pada 1 % dan 4 %, dan lebih ketara penjimatan kos modal 9 %. Kedua-dua metodologi tersebut membolehkan pereka kilang/jurutera untuk menentukan usaha proses pengubahsuaian untuk memperbaiki HI. Perubahan yang dicadangkan kepada proses / aliran perlu dinilai dari perspektif kemungkinan, praktikal dan ekonomi.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ATE - Journal of Applied Thermal Engineering
BFW - Boiler feed water
CC - Composite Curve
CAPEX - Capital expenditure
ChE - Journal of Chemical Engineering
CP - Heat capacity of a stream
CTEP - Journal of Clean Technology and Environmental Policy
CUS - Central Utilities System
CW - Cooling water
CUCC - Cold Utility Composite Curve
$\partial T/\partial H$ - Gradient of segment
DH - District heating
EJ - Exa-joules (10^{18})
ENERGY - Journal of Energy
EU - European Union
ETS - Emission Cap-and-Trade Scheme
FC - Flow control
FOB - Freight on board
GCC - Grand Composite Curve
GHG - Greenhouse gases
Gt - Giga-tonnes
H - Enthalpy
HAZOP - Hazards and operability study
HE - Heat exchanger
HEN - Heat exchanger network
HI - Heat Integration
HO - Hot oil

HPS - High pressure steam
HT - Heat transfer
HTA - Heat transfer area
HTE - Heat transfer enhancement
HUCC - Hot Utility Composite Curve
IF - Impact factor
KCSC - Keep cold stream cold
KHSH - Keep hot stream hot
LC - Level control
LIES - Locally integrated energy sector
LMTD - Log mean temperature difference
LPS - Low pressure steam
MER - Minimum energy requirement
MILP - Mixed integer linear programming
MINLP - Mixed integer non-linear programming
MP - Mathematical Programming
MPS - Medium pressure steam
Mtoe - Million tonnes of oil equivalent
OPEX - Operating expenditure
PA - Pinch Analysis
PC - Pressure control
PRES - International conference on process integration, modeling, optimization for energy saving and pollution reduction
PSE - Process system engineering
PTA - Problem table algorithm
RAM - Reliability, availability and maintenance
SUCC - Site Utility Composite Curve
SP - Site Pinch
SS$_i$P - Site Sink Profile
SS$_o$P - Site Source Profile
SSSP - Site Source-Sink Profiles
STEP - Stream Temperature versus Enthalpy Plot

T-H	-	Turbine-hardware
TC	-	Temperature control
TS	-	Total Site
TSA	-	Total Site Analysis
TS-HSC	-	Total Site heat storage cascade
TS-PTA	-	Total Site problem table algorithm
TSHI	-	Total Site Heat Integration
TSP	-	Total Site Profiles
TSST	-	Total Site sensitivity table
TSUD	-	Total Site utility distribution
U	-	Overall heat transfer coefficient
UFD	-	Utility flow diagram
UGCC	-	Utility Grand Composite Curve
VHPS	-	Very high pressure steam

LIST OF SYMBOLS

A	-	Heat transfer area, m^2
C_{Base}	-	Base cost of fixed head type shell and tube heat exchanger made of carbon steel shell and tubes, USD
C_{Pur}	-	Heat exchanger cost on FOB basis, USD
CP	-	Heat capacity of a stream, MW°/C
d	-	Internal diameter of pipe, mm
fm	-	Moody friction factor
F_M	-	Material factor in HE cost estimate
F_P	-	Pressure factor in HE cost estimate
h_C	-	Corresponding site Sink enthalpies at utilities level, MW
h_H	-	Corresponding site Source enthalpies at utilities level, MW
ΔH	-	Enthalpy change, MW
H	-	Enthaply, MW
LMTD	-	Log mean temperature difference, °C
P	-	Pressure, kPag
ΔP	-	Pressure drop, kPa
Q	-	Heat flow or enthaply, MW
Re	-	Reynolds number
ΔT	-	Temperature change, °C
ΔT_{min}	-	Minimum approach temperature, °C
$\Delta T_{min,PP}$	-	Minimum approach temperature between process and process, °C
$\Delta T_{min,PU}$	-	Minimum approach temperature between process and utility, °C

T^* - Shifted temperature, °C

T^{**} - Double shifted temperature for TSP plot and TS-PTA, °C

T_{Max-So} - Maximum SS_oP temperature on site, °C

T_{Min-So} - Minimum SS_oP temperature on site, °C

T_{Max-Si} - Maximum SS_iP temperature on site, °C

T_{Min-Si} - Minimum SS_iP temperature on site, °C

T_{PH} - The highest Process Pinch temperature on site, °C

T_{PL} - The lowest Process Pinch temperature on site, °C

T_r - Return temperature, °C

T_s - Supply temperature, °C

T_t - Target temperature, °C

U - Overall heat transfer coefficient, MW/m^2°C

V - Velocity, m/s

W - Mass flow, kg/h

Z - Elevation, m

GREEK LETTERS

ε - Pipe roughness factor, m

ρ - Single phase density, kg/m3

SUBSCRIPTS

c - Cold

CV - Control valve

CW - Cooling water

DES - Destination

E - Elevation

f - friction

G	-	Generation
h	-	Hot
H	-	Header
HE	-	Heat exchanger
HO	-	Hot oil
HPS	-	High pressure steam
i	-	Index for temperature interval
j	-	Index for stream
k	-	Index for process
l	-	Liquid
LPS	-	Low pressure steam
MPS	-	Medium pressure steam
P	-	Pipe
PP	-	Process to process
PU	-	Process to utilities
R	-	Requirement
S	-	Steam
SH	-	Sub-header
Si	-	Sink
So	-	Source
TS	-	Total Site
U	-	Usage

CHAPTER 1

INTRODUCTION

1.1 Research Background

Global energy demand is ever increasing due to population growth and economic development of nations. Figure 1.1 shows the total energy demand, in million tonnes of oil equivalent (Mtoe) and the related CO_2 emissions in Giga-tonnes (Gt) from year 1990 to year 201l as well as projections to 2035 (IEA, 2013).

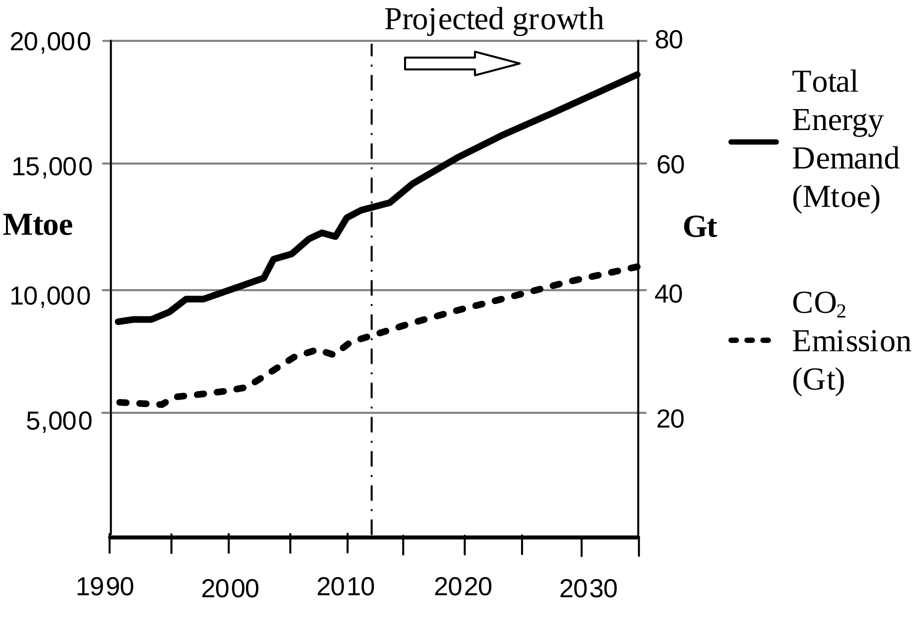

Figure 1.1 Global energy consumption and related CO_2 emission (IEA, 2013)

The global energy demand by fuel is given in Table 1.1. Fossil fuel, i.e. coal, oil and gas accounts for 82% of the energy demand in 2011. Its share is expected to only marginally decline to 80% in 2035 with no change to the current energy and climate change policies. Even if new policies were to be introduced to reduce CO_2 emission and improve energy efficiency, the share of fossil fuel is predicted to slightly reduce by 4% to 76% (IEA, 2013). In essence, fossil fuel will remain as the main resource to meet the global energy demand in the years to come.

Table 1.1: World energy demand by fuel (IEA, 2013)

	Energy demand (Mtoe)			
	2000	2011	2020	2035
Coal	2,357	3,773	4,483	5,435
Oil	3,664	4,108	4,546	5,094
Gas	2,073	2,787	3,335	4,369
Nuclear	676	674	866	1,020
Hydro	225	300	379	471
Bioenergy	1,016	1,300	1,472	1,729
Other renewables	60	127	278	528
Total	10,071	13,070	15,359	18,846
Fossil fuel share	80%	82%	80%	80%
CO_2 emission (Gt)	23.7	31.2	36.1	43.1

Industrial sector is the main energy end-user. Of the 403 EJ (Exa Joule = 10^{18} J) total energy used in 2011, the share of the industrial sector is 51% compared to 20 % by transportation sector, 18% by residential sector and 12% by commercial sector, as depicted in Figure 1.2 (US EIA, 2014).

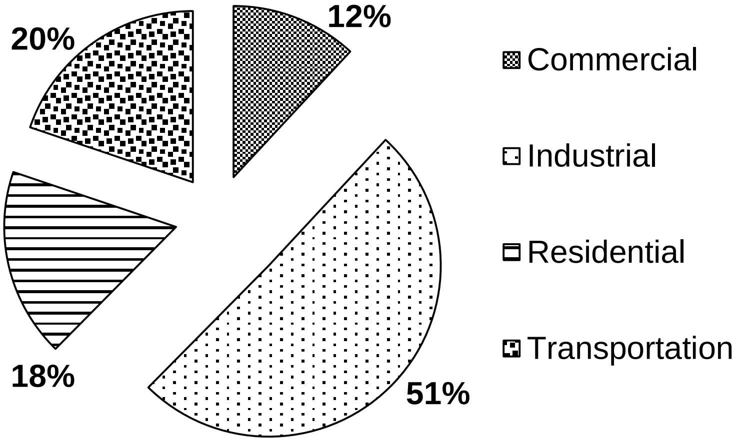

Figure 1.2 Global energy consumption by sector in 2011 (US EIA, 2014)

The main fuel source for the industrial sector is fossil fuel, i.e. oil, coal and gas and these are non-renewable resources. The world fossil fuel resources by fuel type are given in Figure 1.3 (IEA, 2013).

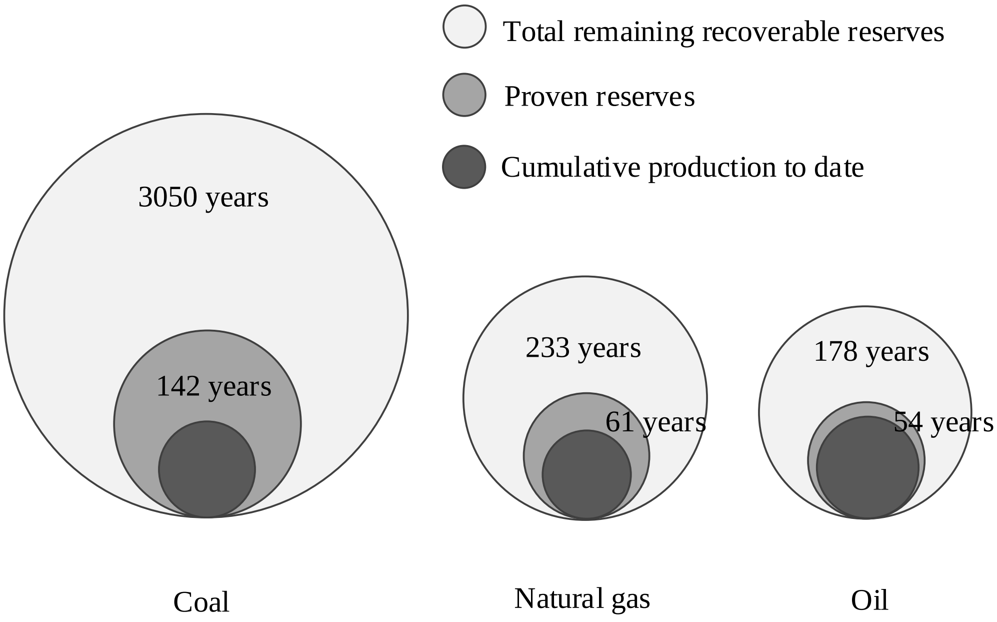

Figure 1.3 Fossil energy resources by type (IEA, 2013)

Fossil-fuel prices are on the increase. Figure 1.4 shows the historical and projected prices of North Sea Brent crude oil (bench mark crude oil) from 1990 to 2040 (US EIA, 2014). Crude oil price can be quite unpredictable. It has fallen sharply from above USD 80 to less than USD 50 per barrel between November 2014 to January 2015 (Nasdaq, 2015). This is even below the “Low Oil Price” scenario forecasted by the US Energy Information Agency (US EIA). Regardless of the crude oil price, which can be fairly volatile, the general trend is that crude oil is likely to be more expensive than cheaper in the long run.

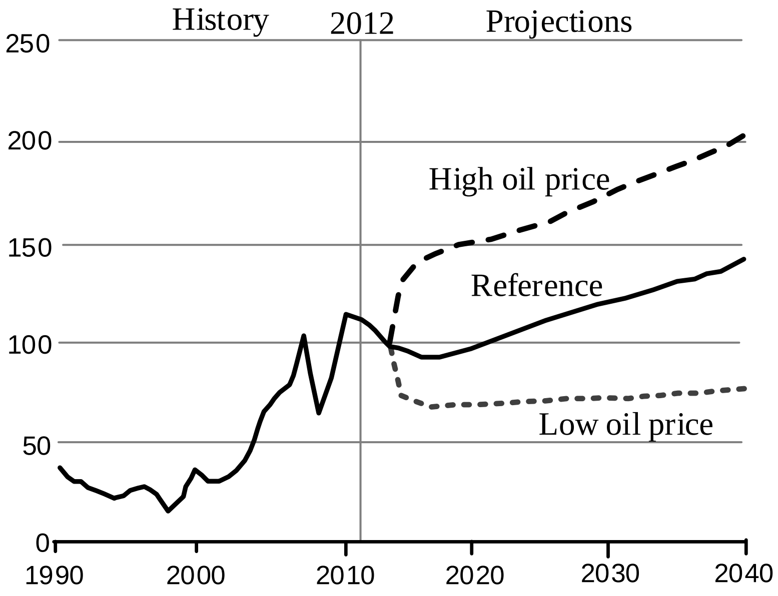

Figure 1.4 North Sea Brent crude oil spot prices in three cases, 1990-2040 (US EIA, 2014)

Rising fuel costs, depleting fossil fuel reserves and increased concerned on global warming have made energy efficiency a necessity. Extensive efforts have been made to improve energy efficiency in the industrial sector. These include the use of recycle or renewable materials as the fuel source, good equipment maintenance programme, improved process control, reduced heat loss, efficient heat integration, adopting more energy efficient processes, etc. (Tanaka, 2011). Energy saving by efficient heat integration remains an essential component of the strategies to improve energy efficiency. Reduced energy usage translates directly to lower fuel requirement and reduced carbon dioxide emissions.

Processes on industrial sites often require large amount of heating, cooling and power generation for their operations. To reduce heating and cooling requirements, heat recovery systems are implemented where applicable. Traditionally, heat integration has typically been confined to heat recovery within a single process. Heat Integration (HI) across different processes is often considered impractical for various reasons. These include the need to reduce interdependency between processes, requirements of flexibility and operability and the large distances between processes. Note however that, there are ample opportunities for energy savings as well as options to overcome constraints, when heat integration potentials among processes on a Total Site (TS) scale are explored.

Total Site Heat Integration (TSHI) has received growing interest since its inception in the 90’s (Klemeš et al, 1997). TSHI is a methodology for integrating heat recovery among multiple processes on a manufacturing site. It optimises the design of the process and utility systems of the entire site at the same time. The methodology has been used to solve models with certain simplifications. In real life implementation, these simplifications may steer the TSHI project towards sub-optimal or non-realistic solutions that can be difficult to fix at the later stage of the project. There has been limited published literature and case studies on the practical implementation of TSHI. An investigation of the main issues that support practical implementation of TSHI is essential to provide a direction for future extension of the TSHI methodology from the industrial perspective.

Pressure drop is an important consideration in TSHI due to the typically large distances between the plants within a TS. Most studies on pressure drop issue are related to retrofit or synthesis of heat exchanger network for a single process. The studies were typically performed using Mathematical Programming approach whereby little insights to the plant designers. The pressure drop factor is addressed in terms of pumping costs, distances, allowable heat exchanger pressure drop or forbidden matches. None of these studies have addressed the pressure drop issue in a TS context which encompasses distance, equipment and utility distribution systems.

The minimum energy targets (Klemeš *et al.*, 1997) in TSHI can be altered by changes in process and/or utilities operating conditions. The impact of utility system changes can be simply deduced as demonstrated in the works of a few researchers

(Hackl *et al.*, 2011; Nemet *et al.*, 2012c; Liew *et al.*, 2014c). However, the impact of process changes on TSHI cannot be easily inferred. In addition, most process modifications are often evaluated within a particular process rather than in TS context. The potential benefits from process modifications for a single process is yet to be fully exploited for TS to improve HI.

1.2 Problem statement

An adequate TSHI design definition is necessary to reduce uncertainty in cost estimate, minimise design changes and improve confidence in expected savings. The main issues that can lead to the practical implementation of TSHI need to be identified and addressed during the early stages of process development.

Current TSHI methodologies have not adequately addressed the pressure drop factor during the MER targeting stage. Exclusion of pressure drop factor when targeting MER may lead to too optimistic energy targets and result in the under-sizing of central utilities system. Neglecting pressure drops in the heat exchanger network (HEN) synthesis may render a proposed design infeasible if the actual pressure drop is higher than what is allowable by pumps and compressors. The need to replace the pumps or compressors may outweigh the savings from HI. It is vital that pressure drop factor in addition to the stream's temperature and heat capacity, be considered.

The Pinch Analysis strategies of modifying Composite Curves to identify process changes to improve HI have been widely practiced for single process but not for TS. The potential of these Pinch strategies for application on TS need to be fully exploited. The TSP can be strategically used to evaluate the potential for further HI improvement to maximise energy saving or reduce heat transfer area (HTA) and its associated capital cost. The TSP can be powerful tool to evaluate potential for further improvement of HI on a TS.

The problem statement of this research is summarized as follows:

Given the process stream temperatures and heat capacities, utility temperatures and plant layout information for a Total Site, it is desired to establish the MER targets which consider the pressure drop factor in order to provide more realistic basis for the design of centralised utility systems. In addition, it is desired to strategically use the TSP to evaluate the potential for further HI improvement to maximise energy savings and/or reduce capital cost of HTA in TSHI.

1.3 Research objective

The main objectives of this study are to extend the TSHI methodology to take into account the pressure drop factor for targeting and design as well as to strategically used the TSP to evaluate potential for further HI improvement to maximise energy savings and/or reduce capital cost of HTA in TSHI. The sub-objectives of this research are to

i. perform a detailed assessment of the existing TSHI methodology for practical TSHI implementation in industries.

ii. develop an improved TSHI methodology which takes into account the pressure drop factor for TSHI targeting and design.

iii. develop a methodology to identify and target process modification of TS to maximise overall site energy savings.

iv. develop a methodology to identify and target process modification of TS to reduce capital cost of HTA in TSHI.

1.4 Research Scope

The scope of this work includes:

i. A Review of TSHI and identifying the research gap.

ii. Assessment of the key issues vital to implementation of practical TSH I projects in the industry.

iii. Development of a spreadsheet based on Pinch Analysis for use as a tool to develop the new methodologies.

iv. Development of a new methodology to consider for pressure drop and its impacts for TSHI targeting and design.

v. Development of a new methodology which applies the Plus-Minus Principle to target process modifications to maximise site energy saving in TSHI.

vi. Development of a new methodology to identify and target process modifications to reduce capital cost of heat transfer units in TSHI.

vii. Method testing and analysis.

1.5 Research Contributions

This research has resulted in the following contributions:

i. A comprehensive assessment of the current TSHI methodology has identified five key issues vital to the practical industrial implementation of TSHI project. By considering these issues in the early stages, practical TSHI solution can be obtained. This assessment has provided a direction for future extension of the TSHI methodology from the industrial perspective.

ii. The TSHI methodology is extended to consider pressure drop, one of the key design issues for TS due to large distances between plants. The improved methodology provides a more realistic basis for the design of central utility systems and the utility circulation pumps.

iii. A methodology which apply the Plus-Minus Principle (Linnhoff *et al.*, 1982) to target process modifications maximise site energy saving in TSHI. This methodology complements the individual process analyses by bringing it within the TS context.

iv. A methodology to identify and target process modifications of TS to reduce capital cost of heat transfer units in HI. The strategic use of the Total Site Profile enables the plant engineers/designers to pinpoint process modification efforts to improve site HI.

A substantial part of the results contained in this thesis have been published in reputable international refereed journals and conferences as listed in Tables 1.2a and 1.2b.

Table 1.2a: Journal and conference paper publications

Title	Type	Status	Contribution towards knowledge
Chew, K.H., Klemeš, J.J., Wan Alwi, S.R., Manan, Z.A. (2013). Issues to be considered for Total Site Heat Integration - An Industrial Perspective. 6th International Conference on Process System Engineering (PSE ASIA). 25-27 June 2013, Kuala Lumpur	International conference	Poster presentation	(i)
Chew, K.H., Klemeš, J.J., Wan Alwi, S.R., Manan, Z.A. (2013). Industrial Implementation Issues of Total Site Heat Integration. *Applied Thermal Engineering*, 61, 17-25.	ISI journal Impact factor: 2.624	Published	(i)
Chew, K.H., Klemeš, J.J., Wan Alwi, S.R., Manan, Z.A., Reverberi, A.P. (2015). Total Site Heat Integration Considering Pressure Drop. *Energies*. 8(2), 1114-1137. doi:10.3390/en8021114	ISI journal Impact factor: 1.602	Published	(i), (ii)
Chew, K.H., Klemeš, J.J., Wan Alwi, S.R., Manan, Z.A. (2013). Process Modification Potentials for Total Site Heat Integration. 16th Conference Process Integration, Modeling and Optimisation for Energy Saving and Pollution Reduction (PRES 2013). 29 September – 2 October 2013, Rhodes, Greece. Chemical Engineering Transactions. 35: 175-180.	International conference Scopus cited	Oral presentation Published	(iii)

Table 1.2b: Journal and conference paper publications

Title	Type	Status	Contribution towards knowledge
Chew, K.H., Klemeš, J.J., Wan Alwi, S.R., Manan, Z.A. (2014). Process modifications to maximize energy savings in Total Site Heat Integration. *Applied Thermal Engineering*. 78, 731-739.	ISI journal Impact factor: 2.624	Published	(iii)
Chew, K.H., Klemeš, J.J., Wan Alwi, S.R., Manan, Z.A. (2014). Process Modification for Capital Cost Reduction in Total Site Heat Integration. 17th Conference Process Integration, Modeling and Optimisation for Energy Saving and Pollution Reduction (PRES 2014). 23-27 August 2014, Prague, Czech Republic. Chemical Engineering Transactions. 39: 1429-1434.	International conference Scopus cited	Poster presentation Published	(iv)
Chew, K.H., Klemeš, J.J., Wan Alwi, S.R., Manan, Z.A. (2014). Process Modification of Total Site Heat Integration Profile for Capital Cost Reduction. *Applied Thermal Engineering.* http://dx.doi.org/10.1016/j.applthermaleng.2015.02.064	ISI journal Impact factor: 2.624	Published	(iv)

1.6 Thesis Outline

This thesis comprise of five chapters. Chapter 1 introduces the research background, problem statement, research objective, scopes and research contributions. A thorough literature review on the development of TSHI is given in Chapter 2. Chapter 3 describes the spreadsheet based graphical algebraic TSHI tool and the three (3) new TSHI methodologies developed. The findings from the detailed assessment of the TSHI methodology for industrial implementation are presented in Chapter 4. Chapter 5 presents the results obtained from the application of developed techniques on case studies. Chapter 6 summarises the major findings of the research and provides recommendations for future research.

REFERENCES

Aguilar, O., Kim, J. K., Perry, S., and Smith, R. (2008). Availability and reliability considerations in the design and optimisation of flexible utility systems. *Chemical Engineering Science*. 63(14), 3569-3584.

Ahmad, S., and Hui, D. C. W. (1991). Heat recovery between areas of integrity. *Computers and Chemical Engineering*. 15(12), 809-832.

Alfa Laval. (2013). *Solves a layout problem and cut costs in a Swiss refinery*. Available from:local.alfalaval.com/en-my/key-industries/oil-refinery-new/downloads/Documents/PPI00048EN.pdf. [accessed on 15-02-2013]

American Petroleum Institute. (2001). *Recommended Practice for Analysis, Design, Installation, and Testing of Basic Surface Safety Systems for Offshore Production Platforms API RP 14C, 7th ed*. Washington, USA: American Petroleum Institute.

Armer, A. (2001). Steam Utilisation. In: Mobley, R.K. (ed.). *Plant Engineer's Handbook*, USA: Elsevier.

Asante, N. D. K., and Zhu, X. X. (1996). An automated approach for heat exchanger network retrofit featuring minimal topology modifications. *Computers and Chemical Engineering*. 20, 1(0), S7-S12.

AspenTech. (2006). *Aspen-HYSYS* (Version 2006) [computer software]. Massachusetts, USA: AspenTech.

Atkins, M. J., Walmsley, M. R. W., and Neale, J. R. (2011). Application of heat recovery loops for Improved Process Integration between Individual Plants at a Large Diary Factory, *Chemical Engineering Transaction*. 25, 183-188.

Bagajewicz, M., and Rodera, H. (2002). Multiple Plant Heat Integration in a Total Site. *American Institute of Chemical Engineers Journal*, 48(10), 16.

Bandyopadhyay, S., Varghese, J., and Bansal, V. (2010). Targeting for cogeneration potential through total site integration. *Applied Thermal Engineering.* 30(1), 6-14.

Becker, H., and Maréchal, F. (2012). Energy integration of industrial sites with heat exchange restrictions. *Computers and Chemical Engineering*. 37(0), 104-118.

Boldyryev, S., Varbanov, P. S., Nemet, A., Klemeš, J. J., and Kapustenko, P. (2014) Minimum heat transfer are for Total Site Heat Integration. *Energy Conversion and Management*. 87, 1093-1097.

Cheung, K. Y., and Hui, C. W. (2004). Total-site scheduling for better energy utilization. *Journal of Cleaner Production*. 12(2), 171-184.

Chew, K.,H., Klemeš, J. J., Wan Alwi, S. R., and Abdul Manan, Z. (2013). Industrial implementation issues of Total Site Heat Integration, *Applied Thermal Engineering.* 61, 17-25.

Choudhury, A. A. S., Nwaoha, C., and Vishwasrao, S. (2012). Valves. In: Holloway M.D., Nwaoha C.N., and Onyewuenyi O.A. (eds.). *Process Plant Equipment: Operation, Control and Reliability,* New York, USA: Wiley.

Ciric, A. R., and Floudas, A. C. (1990). A mixed integer nonlinear programming model for retrofitting heat-exchanger network. *Industrial and Engineering Chemistry*. 29, 239-251.

Couper, J. R., Penney, W. R., Fair, J. R., and Wales, S. M. (2012). *Chemical Process Equipment - Selection and Design*. 3rd Edition. New York, USA: Butterworth-Heinemann

Crane Co. (1988). *Flow of fluids through valves, fittings and pipe*, Technical Paper No. 410.

DeGarmo, E. P., Sullivan, W. G., Bontadell, J. A., and Wicks, E. M. (1997). *Engineering Economy*. 10th Edition. New Jersey: Prentice-Hall International Inc.

Dhole, V. R., and Linnhoff, B. (1993). Total site targets for fuel, co-generation, emissions, and cooling. *Computers and Chemical Engineering.* 17, Supplement 1(0), S101-S109.

El-Halwagi, M. M., Gabriel, F., and Harell, D. (2003). Rigorous graphical targeting for resource conservation via material recycle/reuse networks. *Industrial & Engineering Chemistry Research.* 42, 4319-4328.

European Union (EU). (2013a). *Council Directive 92/42/EEC - Efficiency requirements for new hot-water boilers fired with liquid or gaseous fuels.* Available from: eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX :31992L0042:en:NOT. [accessed on 21-02-2013]

European Union (EU). (2013b). *Directive 2010/31/EU – Energy performance of buildings*. Available from: eur-lex.europa.eu/LexUriServ/LexUriServ. do?uri=OJ:L:2010:153:0013:0035:EN:PDF. [accessed on 21-02-2013]

European Union (EU). (2013c). *Directory of European Union legislation in force – Energy*. Available on: eur-lex.europa.eu/en/legis/latest/index.htm. [accessed on 15-02-2013]

Feng, X., Pu, J., Yang, J., and Chu, K. H. (2011). Energy recovery in petrochemical complexes through heat integration retrofit analysis. *Applied Energy*. 88(5), 1965-1982.

Fodor, Z., Perry, S., Varbanov, P., and Klemeš, J. (2010). Total site targeting accounting for individual process heat transfer characteristics. *Chemical Engineering Transaction.* 21, 2010, 49-54.

Ghannadzadeh, A., Perry, S., Smith, R. (2012). Cogeneration targeting for site utility systems. *Applied Thermal Engineering*. 43(0), 60-66.

Goršek, A., Glavič, P., and Bogataj, M. (2006). Design of the optimal total site heat recovery system using SSSP approach. *Chemical Engineering and Processing: Process Intensification*. 45(5), 372-382.

GreenTech Malaysia. *National Energy Policy, Incentives and Regulations.* Available on: www.greentechmalaysia.my. [accessed 4-10-2012]

Hackl, R., Andersson, A., and Harvey, S. (2011). Targeting for energy efficiency and improved Energy collaboration between different companies using total site analysis (TSA). *Energy,* 36 (8) 4609-4615.

Hackl, R., and Harvey, S. (2013). Applying exergy and total site analysis for targeting refrigerant shaft power in industrial cluster. *Energy.* 55, 5-1.

Hall, S. G., Ahmad, S., and Smith, R. (1990). Capital cost targets for heat exchanger networks comprising mixed materials of construction, pressure ratings and exchanger types. *Computers and Chemical Engineering.* 14(3), 319-335.

Hallale, N., and Liu, F. (2001). Refinery hydrogen management for clean fuels production. *Advances in Environmental Research*. 6(1), 81-98

Hirata, K., Sakamoto, H., O'Young, L., Cheung, K. Y., and Hui, C. W. (2004). Multi-site utility integration—an industrial case study. *Computers and Chemical Engineering*. 28(1–2), 139-148.

Hohmann, E. C. (1971). *Optimum networks for heat exchange.* PhD Doctor Philosophy. University of Southern California Los Angeles, USA.

International Energy Agency (IEA). (2013). *World Energy Outlook, 2013*. Available on: www.iea.org/Textbase/npsum/WEO2013SUM.pdf. [Accessed on 12-12-2014]

Kang, C. A., Brandt, A. R., and Durlofsky, L. J. (2011). Optimal operation of an integrated energy system including fossil fuel power generation, CO2 capture and wind. *Energy*, 36(12), 6806-6820.

Kapil, A., Bulatov, I., Smith, R., and Kim, J.K. (2012). Process integration of low grade heat in process industry with district heating networks. *Energy*. 44(1), 11-19.

Karimkashi, S., and Amidpour, M. (2012). Total site energy improvement using R-curve concept. *Energy*, 40, 329-340.

Kementerian Tenaga, Teknologi Hijau dan Air (KeTTHA), Malaysia. (2012). *National Energy Policy*. Available on: www.kettha.gov.my/en. [Accessed 4-10-2012]

Kemp, I. C. (2007). *Pinch analysis and process inregration. A user guide on process integration for the efficient use of energy*. 2nd Edition. UK: Institution of Chemical Engineer.

Kemp, I. C., and Deakin, A. W. (1989). The cascade analysis for energy and process integration of batch processes. *Chemical Engineering Research and Design.* 67, 495-509.

Kenny, W. F. (1984). *Energy conservation in process industries*. Orlando, USA: Academic Press.

Klemeš, J., Friedler, F., Bulatov, I., and Varbanov, P. (2010). *Sustainability in the Process Industry - Integration and Optimisation.* New York: McGraw-Hill.

Klemeš, J., Dhole, V. R., Raissi, K., Perry, S. J., and Puigjaner, L. (1997). Targeting and design methodology for reduction of fuel, power and CO2 on total sites. *Applied Thermal Engineering*. 17(8–10), 993-1003.

Klemeš, J., and Varbanov, P. (2010). Implementation and Pitfalls of Process Integration. *Chemical Engineering Transactions*. 21, 1369-1374.

Klemeš J.J., and Kravanja, Z. (2013). Forty years of Heat Integration: Pinch Analysis (PA) and Mathematical Programming (M)), *Current Opinion in Chemical Engineering*. 2, 461-474.

Klemeš J.J., Varbanov, P.S., and Kravanja, Z. (2013). Recent development in Process integration, *Chemical Engineering Research and Design*. 91, 2037-2053.

Liew, P. Y., Wan Alwi, S. R., Varbanov, P. S., Manan, Z. A., and Klemeš, J. J. (2012). A Numerical Technique for Total Site Sensitivity Analysis. *Applied Thermal Engineering*. 40(0), 397-408.

Liew, P. Y., Wan Alwi, S. R., Varbanov, P. S., Manan, Z. A., and Klemeš, J. J. (2013). Centralised utility system planning for Total Site Heat Integration Network.*Computers & Chemical Engineering*. 57, 104-111

Liew, P. Y., Wan Alwi, S. R., Klemeš, J. J., Varbanov, P. S., and Manan, Z. A. (2014a). Algorithmic target for Total Site Heat Integration with variable energy supply/demand. *Applied Thermal Engineering*. 70, 1073-1083.

Liew, P. Y., Wan Alwi, S. R., and Klemeš, J. J. (2014b). Total Site Heat Integration targeting algorithm incorporating plant layout issues. *Computer Aided Chemical Engineering*. 33, 1801-1806.

Liew, P. Y., Lim, J. S., Wan Alwi, S. R., Manan, Z. A., Varbanov, P. S., and Klemeš, J. J. (2014c). A retrofit framework for Total Site heat recovery systems. *Applied Energy*. 135, 778-790.

Linnhoff, B., and Flower, J. R. (1978). Synthesis of heat exchanger networks. 2 Parts. Part I: Systematic generation of energy optimal networks. Part II: Evolutionary generation of networks with various criteria of optimality. *American Institue of Chemical EngineersJournal*. 24(4), 633-642.

Linnhoff, B., Mason, D. R., and Wardie, I. (1979). Understanding heat exchanger networks. *Computers and Chemical Engineering*. 3(1-4), 195-302.

Linnhoff, B., Townsend, D. W., Boland, D., Hewitt, G. F., Thomas, B. E. A., Guy, A. R., and Marsland, R. H. (1982). *A user guide on process integration for the efficient use of energy*. Rugby, UK: Institution of Chemical Engineer.

Linnhoff, B., and Hindmarsh, M. (1983). The pinch design method for heat exchanger networks. *Chemical Engineering Science*. 38(5), 745-763.

Linnhoff, B., and Vredeveld, D. R. (1984). Pinch technology has come of age, *Chemical Engineering Progress*, 80(7), 33-40.

Linnhoff M. (1998). *Introduction to pinch technology*. Northwich, UK: Linnhoff March.

Makwana, Y., Smith, R., and Zhu, X. X. (1998). A novel approach for retrofit and operations management of existing total sites. *Computers and Chemical Engineering*. 22, 1(0), S793-S796.

Manesh, M. H. K., Abadi, S. K., Amidpour, M., and Hamedi, M. H. (2013). A new targeting method for estimation of cogeneration potential and total annualized cost in process industries. *Chemical Engineering Research and Design*. 91(6), 1039-1049.

Matsuda, K., Hirochi, Y., Tatsumi, H., and Shire, T. (2009). Applying heat integration Total site based pinch technology to a large industrial area in Japan to further improve performance of highly efficient process plant. *Energy*. 34, 1687-1692.

Matsuda, K., Tanaka, S., Endou, M., and IIyoshi, T. (2012a). Energy saving study on a large steel plant by total site based pinch technology. *Applied Thermal Engineering*. 43, 14-19.

Matsuda, K., Kurosaki, D., Hayashi, D., and Aoyama, K. (2012b). Industrial Heat Pump Study using Pinch technology for Large Scale Petrochemical Site. *Chemical Engineering Transactions*. 29, 67–72.

Marechal, F., and Kalitventzeff, B. (1997). Identification of the optimal pressure levels in steam network using integrated combined heat and power method. *Chemical Engineering Science*. 52(17), 2977-2989.

Mavromatis, S. P., and Kokossis, A. C. (1998). Conceptual optimisation of utility networks for operational variations—I. targets and level optimisation. *Chemical Engineering Science*. 53(8), 1585-1608.

Nasdaq. (2015). *Latest Commodity Prices - Crude Oil* . Available on: www.nasdaq.com/markets/crude-oil.aspx?timeframe=3m. [accessed 31-01-2015]

Nemet, A., Boldyryev, S., Varbanov P. S, Kapustenko, P., and Klemeš, J. (2012a). Capital cost targeting of Total Site heat recovery. *Chemical Engineering Transactions*. 29, 1447-1452.

Nemet, A., Klemeš, J. J., Varbanov, P. S., and Kravanja, Z. (2012b). Methodology for maximising the use of renewables with variable availability. *Energy*, 44(1), 29-37.

Nemet, A., Klemeš, J., Varbanov P. S, Atkins M., and Walmsley M. (2012c). Total Site Methodology as a Tool for Planning and Strategic Decisions, *Chemical Engineering Transactions*. 29, 115-120

Nemet, A., Klemeš, J. J., and Kravanja, Z. (2015). Designing a Total Site for an entire lifetime under flucatuating utility prices. *Computers and Chemical Engineering*, 72, 159-182.

Nie, X. R., Zhu, X. X. (1999). Heat exchanger network retrofit considering pressure drop and heat transfer enhancement. *American Institute of Chemical Engineer Journal*. 45, 1239.

Panjaeshahi, M. H., and Tahouni, N. (2008). Pressure optimisation in debottlenecking of heat exchanger networks. *Energy*. 33, 942-951.

Perry, S., Klemeš, J., and Bulatov, I. (2008). Integrating waste and renewable energy to reduce the carbon footprint of locally integrated energy sectors. *Energy*. 33(10), 1489-1497.

Polley, G. T., Panjehshahi, M. H., and Jegede, F.O. (1990). Pressure drop considerations in the retrofit of heat exchanger networks. *Chemical Engineering Research and Design*. 68(A3), 211-220.

Pourali, O., Amidpour, M., and Rashtchian, D. (2006). Time decomposition in batch process integration. *Chemical Engineering and Processing: Process Intensification*. 45(1), 14-21.

Pouransari, N., and Marechal, F. (2014). Heat exchanger network design of large-scale industrial site with layout inspired constraints. *Computers and Chemical Engineering*. 71, 426-445.

Querzoli, A. L., Hoadley, A. F. A., and Dyson, T. E. S. (2003). Identification of Heat Integration Retrofit Opportunities for Crude Distillation and Residue Cracking Units. *Korean Journal of Chemical Engineer.* 20(4), 635-641.

Raissi, K. (1994). *Total Site Integration.* PhD Doctor Philosophy, University of Manchester Institute of Science and Technology, Manchester, UK.

Rozali, M. N. E., Wan Alwi, S. R., Manan, A. Z., Klemeš, J. J., and Hassan, M. Y. (2014). Optimal sizing hybrid power systems using power pinch analysis. *Journal of Cleaner Production*. 71, 158-167.

Sinnot, R. K. (2005). *Chemical Engineering Design, in: Coulson and Richardson's Chemical Engineering*. Volume 6. 4th Edition. Oxford: Elsevier Butterworth-Heinemann.

Smith, R. (2005). *Chemical Process Design and Integration.* Oxford: John Wiley and Sons.

Smith, R., Yin, Q., Lin, Z., and Zheng, X. (2011). Reliability issues in the design and operation of process utility systems. *Chemical Engineering Transactions*. 22, 75-80.

Spirax Sarco. (2014). *Pipes and Pipe sizing*. Available from: www.spiraxsarco.com/resources/steam-engineering-tutorials/steam-distribution/pipes-and-pipe-sizing.asp. [accessed 23-9-2014]

Soltani, H., and Shafiei, S. (2011). Heat exchanger networks retrofit with considering pressure drop by coupling genetic algorithm with LP (linear programming) and ILP (integer linear programming) methods. *Energy*. 36, 2381-2391.

Sorsak, A., and Kranvanja, Z. (1999). Simultaneous MINLP synthesis of heat and power integrated heat exchanger network, *Computer and Chemical Engineering Supplement*. S143-S147.

Sorin, M., and Hammache, A. (2005). A new thermodynamic model for shaftwork targeting on total sites. *Applied Thermal Engineering.* 25(7), 961-972.

Tan R. R., and Foo, D. C. Y. (2007). Pinch analysisto carbon-constrained energy sector planning. *Energy*. 32(8), 1422-1429.

Tanaka, K. (2011). Review of policies and measures for energy efficiency in industry sector. *Energy Policy.* 39(10), 6532-6550.

Townsend, D. W., and Linnhoff, B. (1983). Heat and power network in process design. Part II: Design procedure for equipment selection and process matching. *American Institute of Chemical Engineers Journal.* 29(5),748-771.

U.S. Energy Information Administration (EIA). (2013). *International Energy Outlook 2013*. Available on: www.eia.gov/forecasts/ieo/pdf/0484(2013).pdf. [Accessed on 15-12-2014]

Varbanov, P., Perry, S., Makwana, Y., Zhu, X. X., and Smith, R. (2004). Top-level Analysis of Site Utility Systems. *Chemical Engineering Research and Design.* 82(6), 784-795.

Varbanov, P. S., Fodor, Z., and Klemeš, J. J. (2012). Total Site targeting with process specific minimum temperature difference (ΔTmin). *Energy,* 44(1), 20-28.

Varbanov, P. S., Doyle, S., and Smith, R. (2004). Modelling and optimisation of utility systems. *Transaction of IChemE - Chemical Engineering Research and Design.* 82(A5), 561-578.

Varbanov, P. S., and Klemes, J. J. (2010). Total Sites Integrating Renewables With Extended Heat Transfer and Recovery. *Heat Transfer Engineering.* 31(9), 733-741.

Varbanov, P. S., and Klemeš, J. J. (2011). Integration and management of renewables into Total Sites with variable supply and demand. *Computers and Chemical Engineering.* 35(9), 1815-1826.

Walmsley, T.G., Walmsley, M.W.W., Atkins, M.J., and Neale, J.R. (2013). Improving energy recovery in milk powder production through soft data optimisation. *Applied Thermal Engineering*. 61(1), 80-87.

Wan Alwi, S. R., Mohammad Rozali, N. E., Abdul-Manan, Z., and Klemeš, J. J. (2012). A process integration targeting method for hybrid power systems. *Energy.* 44(1), 6-10.5

Wan Alwi, S. R., Lee, M. L., Lee, K. Y., Abd Manan,, Z., and Fraser, D. M. (2014) Targeting the maximum heat recovery for systems with heat losses and heat gains. *Energy Conservation and Management*. 87, 1098-1106

Wang, Y. P., and Smith, R. (1994). Wastewater Minimisation. *Chemical Engineering Science*. 49(7), 981-1006.

Wang, Y., Feng, X., and Chu, K. H. (2014). Trade-off between energy and distance related costs for different connection patterns in heat integration across plants. *Applied Thermal Engineering.* 70, 857-866

Wien Energie Group – Fernwärme Wien, (2009). *District Heating and Cooling in Vienna – The "Vienna Model".* Available on: www.copenhagenenergysummit.org /applications/Vienna,%20Austria-District%20Energy%20Climate%20Award.pdf. [accessed 14-12-2012]

Yee, T.F., and Grossman, I.E. (1990). Simultaneous optimisation models for heat integration – II. Heat exchanger network synthesis, *Computer and Chemical Engineering*. 14, 1165-1184.

Zhao, X. G., O'neill, B. K., Roach, J. R., and Wood, R. M. (1998). Heat Integration For Batch Processes: Part 1: Process Scheduling Based on Cascade Analysis. *Chemical Engineering Research and Design*. 76(6), 685-699.

Zhelev, T. K., and Bhaw, N. (2000). Combined water-oxygen pinch analysis for better wastewater treatment management. *Waste Management*. 20(8), 665-670.

Zhelev, T., and Ntlhakana, L. (1999). Energy-environment closed loop through oxygen pinch. *Computers and Chemical Engineering*. 23(Suppl.), 79-83.

Zhelev, T. K., and Ridolfi, R. (2006). Energy recovery and environmental concerns addressed through emergy–pinch analysis. *Energy, 31*(13), 2486-2498.

Zhu, X. X., Zanfir M., and Klemeš, J. J. (2000). Heat Transfer Enhancement for Heat Exchanger Network Retrofit, *Heat Transfer Engineering*. 21, 7-18.

Zhu, X.X., Nie, X.R. (2002). Pressure drop considerations for heat exchanger network grassroots design, *Computers and Chemical Engineering*. 26, 1661, 1676.