SEGREGATED PROBLEM TABLE ALGORITHM FOR SIMULTANEOUS TARGETING AND DESIGN OF INTEGRATED ENERGY NETWORKS

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requirements for the award of the degree of
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To my beloved parents, brother and sister

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ABSTRACT

Pinch analysis is an established methodology for process design and optimization to achieve the minimum utility consumption. The Problem Table Algorithm (PTA) is one of the most popular numerical methods to determine the energy targets. However, the PTA is unable to show the individual hot and cold stream heat cascade profile. This work presents a new numerical tool for simultaneous targeting and design of heat exchanger networks called the Segregated Problem Table Algorithm (SePTA). SePTA, which shows individual hot and cold streams heat cascade profiles across temperature intervals, allows a designer to simultaneously determine the energy targets, locate the pinch points and perform the SePTA Heat Allocation (SHA). This work also extends the use of SePTA for process integration of a trigeneration system. Using SePTA, appropriate matching of heat engines and heat pumps with process streams can be made. Process integration with trigeneration has been implemented in a case study involving edible palm oil plant to reduce demands for heating, cooling as well as power consumptions. The results have been compared to a system without trigeneration, and those with a heat engine as well as a heat pump. The trigeneration system is able to fulfill 3990kW of hot utility for the process and 1241kW of driving energy required by an absorption heat pumps's generator. At the same time, 238kW electricity is produced by the turbine and 185kW is saved from the shut down of one unit chiller for a compressor. Trigeneration integration with process led to an annual savings of RM 1.1 mil with an investment payback period of 1.9 years.

ABSTRAK

Analisis jepit adalah kaedah bagi rekabentuk proses dan pengoptimuman untuk mencapai penggunaan utiliti minimum. *Problem Table Algorithm* (PTA) adalah kaedah berangka yang paling popular untuk menentukan sasaran tenaga. Walau bagaimanapun, PTA tidak dapat menunjukkan haba lata profil untuk aliran individu yang panas dan sejuk. Kerja ini membentangkan alat berangka baru dipanggil *Segregated Problem Table Algorithm* (SePTA) untuk penyasaran serentak dan rekabentuk rangkaian penukar haba. SePTA menunjukkan haba lata profil untuk aliran individu yang panas dan sejuk merentasi selang suhu, membolehkan pereka menentukan sasaran tenaga and mentukan *pinch point* secara serentak dan melaksanakan *SePTA Heat Allocation* (SHA). Kerja ini juga merangkumi penggunaan SePTA untuk integrasi proses sistem tri-generasi. Menggunakan SePTA, padanan yang sesuai untuk enjin haba dan pam haba degan aliran proses boleh dilakukan. Proses integrasi dengan sistem tri-generasi telah dilaksanakan dalam kajian kes yang melibatkan perindustrian minyak kelapa sawit yang boleh makan untuk pengurangan permintaan untuk pemanasan, penyejukan serta penggunaan kuasa. Hasil kajian ini akan dibandingkan dengan sistem tanpa tri-generasi, dan bahawa dengan enjin haba dan pam haba. Sistem tri-generasi dapat memenuhi 3990kW utiliti panas untuk proses dan 1241kW tenaga yang diperlukan oleh penjana pada sistem pendingin jenis penyerapan. Pada masa yang sama, elektrik 238kW dapat dihasilkan oleh turbin dan 185kW dapat jimat dari menutup 1 unit sistem pendingin jenis pemampat. Integrasi tri-generasi dengan proses boleh membawa penjimatan tahunan sebanyak RM1.1 juta dan bayar balik tempoh dalam 1.9 tahun.

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LIST OF SYMBOLS

DH	–	Net enthalpy
FCp	–	Heat capacity flowrate (kW/^{o}C or MW/^{o}C)
h_L	–	Specific enthalpy of pure lithium bromide (kJ/kg)
h_w	–	Specific enthalpy of pure water (kJ/kg)
$h_{w,liquid}$	–	Specific enthalpy of liquid water (kJ/kg)
$h_{w,sup}$	–	Enthalpy of superheated water vapor
H^l	–	Liquid enthalpy (kJ/kg)
H^v	–	Vapor enthalpy (kJ/kg)
kW	–	Kilowatt
M_L	–	Molecular weights of anhydrous lithium bromide (kg/kmol)
M_w	–	Molecular weights of water (kg/kmol)
m	–	Mass flow rate of refrigerant (kg/s)
m_L	–	Mass of anhydrous lithium bromide in solution (kg)
m_{ss}	–	Mass flow rate of strong solution (kg/s)
m_w	–	Mass of a water in solution (kg)
m_{ws}	–	Mass flow rate of weak solution (kg/s)
n_L	–	Number of moles of anhydrous lithium bromide in solution (mol)
n_w	–	Number of moles of water in solution (mol)
Qa	–	Heat of absorption (kW)
Qg	–	Heat of generation (kW)
Qc	–	Heat of condenser (kW)
Qe	–	Heat of evaporation (kW)
Q_{Hmin}	–	Minimum hot utility requirement (kW or MW)
Q_{Cmin}	–	Minimum cold utility requirement (kW or MW)
S^l	–	Liquid entropies (kJ/kg)
S^v	–	Vapor entropies (kJ/kg)

Tc'	–	Cold streams shifted temperature (^oC)
Th'	–	Hot streams shifted temperature (^oC)
Ts	–	Supply temperature (^oC)
Tt	–	Target temperature (^oC)
Ts'	–	Supply shifted temperature (^oC)
Tt'	–	Target shifted temperature (^oC)
T-H profile	–	Temperature enthalpy profiles
ΔTmin	–	Minimum approach temperature (^oC)
W	–	Work
Q	–	Heat
η_{isen}	–	Isentropic efficiency (%)
H_2O	–	Water
LiBr	–	Lithium bromide
NH_3	–	Ammonia
ξ	–	Mass fraction
x	–	Mole fraction
λ	–	Circulation ratio
ξss	–	Mass fraction of strong solution
ξws	–	Mass fraction of weak solutio

LIST OF ABBREVIATIONS

AHP	–	Absorption heat pump
CA	–	Cold stream above the pinch point
CC	–	Composite curve
CHW	–	Chilled water
COP	–	Coefficient of performance
CPU	–	Combined process and utility
Cum	–	Cumulative
CW	–	Cooling water
DT	–	Temperature intervals
EGCC	–	Extended grand composite curve
GCC	–	Grand composite curve\
HA	–	Hot stream above the pinch point
HB	–	Hot stream below the pinch point
HEN	–	Heat exchanger network
HQCHW	–	High quality chilled water
H-S diagram	–	Enthalpy entropy diagram
LP	–	Linear programming
LPS	–	Low pressure steam
LR	–	Lagrangian relaxation
NPV	–	Net present value
NPW	–	Net present worth
PRV	–	Pressure reducing valve
PTA	–	Problem table algorithm
SePTA	–	Segregated problem table algorithm
SPB	–	Simple payback time
SPTA	–	Simple problem table algorithm

STEP	–	Streams temperature vs enthalpy plot
TCS	–	Tri-commodity simplex
TPES	–	Trigeneration Primary Saving
TW	–	Tempered water

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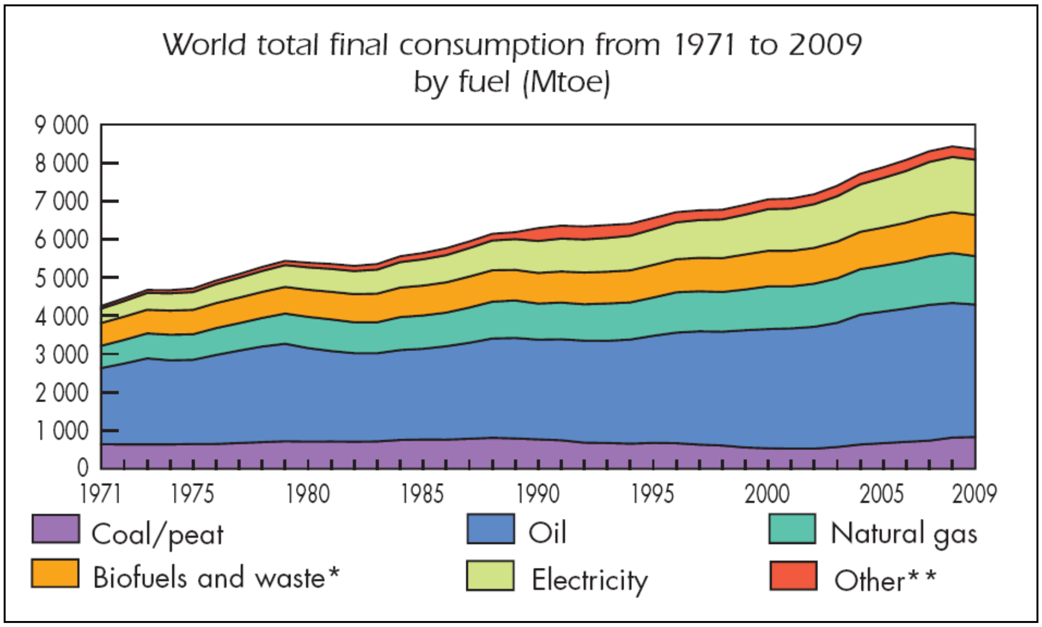
CHAPTER 1

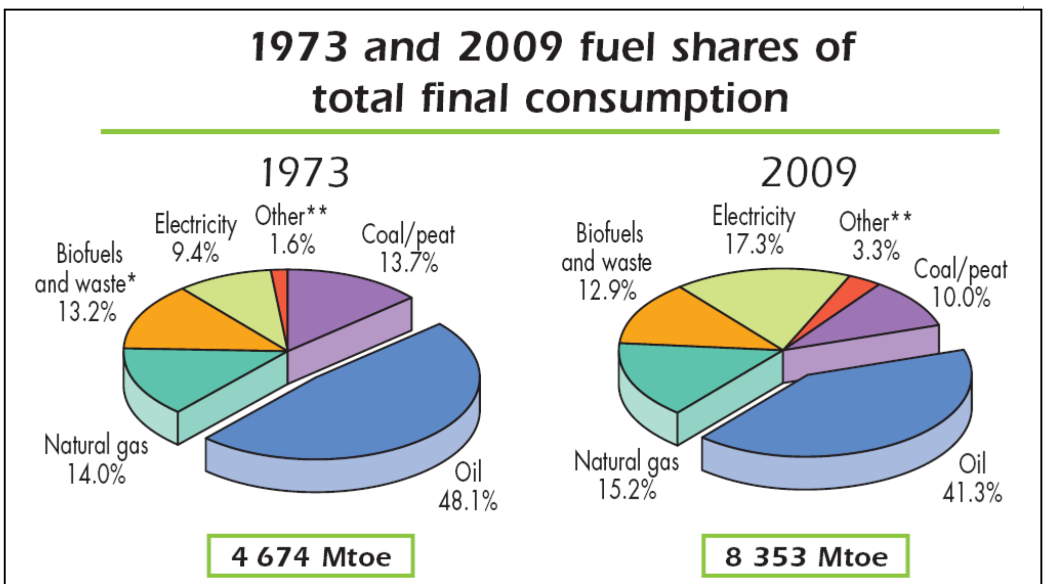
INTRODUCTION

1.1 Introduction

Since the beginning of the industrial revolution in the 17^{th} century, the growth in the world economy leads to the increased use of energy. It is reported that the fossil fuel consumption rose by 57 percent between 1973 and 2009. In 2009, the total worldwide energy consumption was 8353 Mtoe (million tones oil equivalent) with 67 percent derived from the combustion of fossil fuels (Figure 1.1) (International Energy Agency,2011).



(a)



(b)

Figure 1.1: (a) Evolution from 1971 to 2009 of world total final consumption by fuel (Mtoe) and (b) 1973 and 2009 fuel shares of total final consumption (International Energy Agency, 2011)

The finite amount of fossil fuel coupled with therapid rate of fossil fuel consumption lead to fossil fuel depletion. The Energy Watch Group (EWG) reports that, the oil supply may be insufficient (Energy Watch Group, 2007) and non renewable energy such as uranium resources would be exhaust within 70 years (Energy Watch Group, 2006). The International Energy Agency (EIA) also reported that the coal reserves are around 998 billon tonnes which could sustain the current production rate for 164 years. However, with 5% growth in consumption per annum, the coal reserve is only expected to last until the year 2051 (Energy Watch Group, 2007).

Increase in world energy consumption not only increases the rate of fossil fuel depletion, it also governs the greenhouse gas emissions to the atmosphere and subsequently causes global warming. The global carbon dioxide emission has increase by 107 percent between 1971 and 2009. In the year 2009, it has been recorded that the carbon emission was high as 29,000 metric tons of carbon (Figure 1.2) (International Energy Agency, 2011).

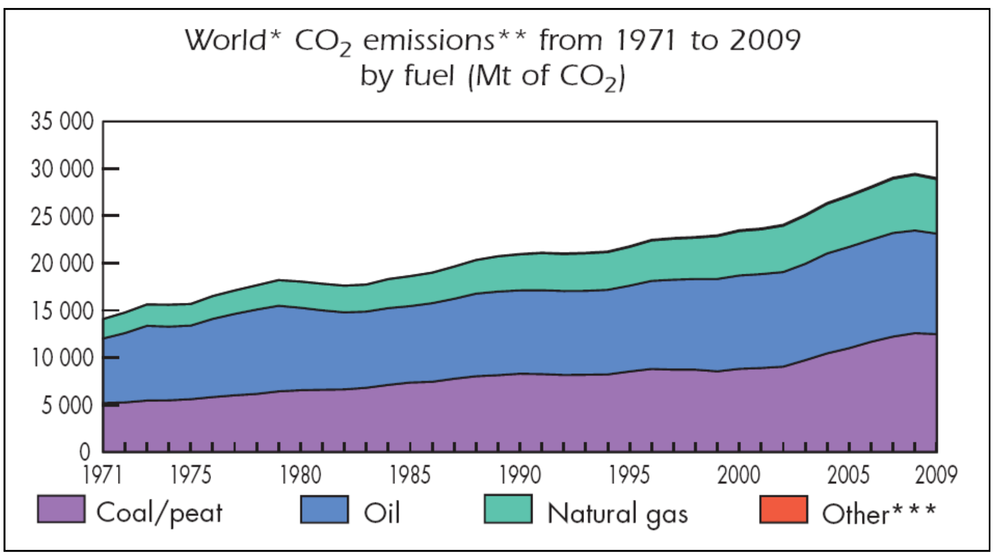


Figure 1.2: World carbon dioxide emissions from 1971 to 2009 by fuel (Mt of CO_2) (International Energy Agency, 2011)

The US Environmental Protection Agency (USEPA) presented the inventory of U.S greenhouse gas emissions and sinks based on the common economic sector (Figure 1.3). Its shows that, the emissions from the electricity generation produce the largest portion of greenhouse gas to the environment from year 1990 to 2006, followed by the transportation and industry sector. The agriculture, commercial and residential economic sectors emission only shows one quarter of the electricity generation sector.

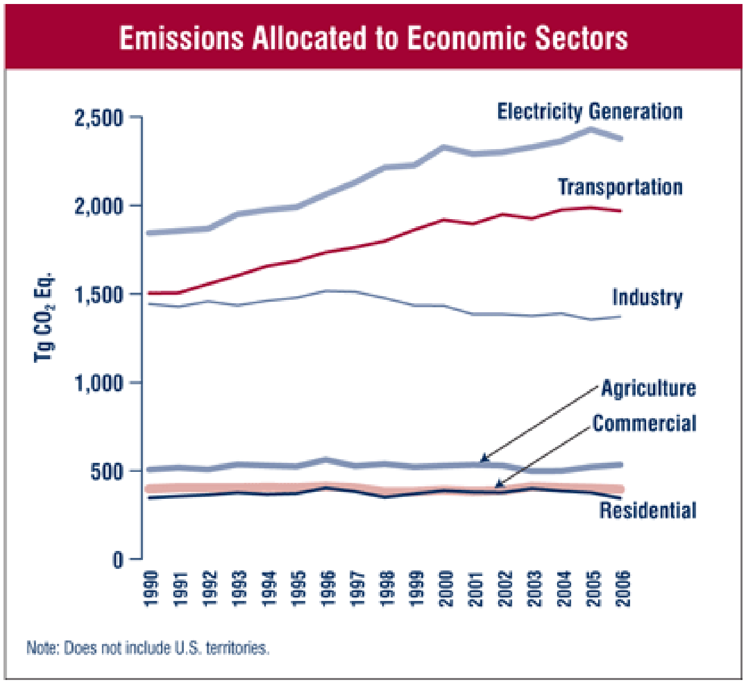


Figure 1.3: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2006 (U.S Environmental Protection Agency, 2008)

The large quantity of green house gas emissions is causing serious global warming impacts. Over the last 50 years, the southern part of the Arctic region at northern hemisphere has experienced the temperature rise of between 1 ^oC to 3 ^oC. It was projected that global warming may cause an increase in average temperature of the earth by 0.74±0.18 °C between early and by the end of 20th century (Intergovernmental Panel on Climate Change, IPPC, 2007).

Reducing energy consumption can contribute towards reducing global warming. Since the industry is the main sector causing the greenhouse gas emissions, it becomes important for industries to look for effective technologies to reduce energy consumption as well as harmful environmental emissions. Over the past 20 years, pinch analysis has been used as a tool for the optimal design of heat, power, water, mass, hydrogen recovery networks (Natural Resources Canada, 2008). Heat pinch analysis, which is the oldest pinch analysis application, provides tools for maximizing heat recovery and minimizing the demand for external utilities using graphical techniques such as the Composite Curves (CCs) and numerical techniques such as the Problem Table Algorithm (PTA) (Linnhoff & Flower, 1978; Linnhoff *et al.,* 1982; Linnhoff-March Limited, 1992; Smith, 1995; Kemp, 2007). In determining the energy targets and the pinch points, the PTA is typically preferred to drawing the CCs because of its advantages in terms of accuracy and speed, and due to its amenability to computer programming.

To date, there has been an increased interest on the use of energy-efficient tool such as cogeneration as well as trigeneration systems. Cogeneration system refers to the combined production of electrical and thermal energy by utilization of the same fuel. Trigeneration, on the other hand have the additional advantage of generating cooling energy apart from electrical and thermal from utilization of the same fuel. To enhance the energy savings potential, pinch analysis tools such as the Grand Composite Curve (GCC) which is generated from the PTA has been used for process integration with trigeneration systems (Calva *et al.,* 2005 and Marinova *et al.,* 2007).

1.2 Problem Background

The PTA is an efficient and popular alternative for CCs as it uses algebraic/numerical calculations which are more accurate and exact. The minimum approach temperature (ΔT_{min}) in PTA ensures a minimum driving force, and hence, feasible heat exchange between hot and cold streams in a given temperature interval range. The PTA approach essentially lumps the hot and cold streams enthalpy and cascades the net heat surplus or deficit to intervals at lower temperatures. However, due to this lumping process, the PTA does not fully show the individual hot and cold streams heat cascade profile. Hence, PTA cannot guide individual "process to process" or "process to utility" streams matching.

The GCC generated from PTA is unable to show the individual hot and cold streams heat cascade profile, and also unable to guide the individual "process to process" or "process to utility" streams matches. Thus, heat engines and heat pumps position cannot be exactly pinpointed to process and utility streams. In addition, most of the trigeneration system configuration selections are based on the economic analysis without considering the overall process, it may cause higher energy requirements than the theoretical minimum requirements even though with the low investment cost and higher revenue.

Most of the works on mathematical programming and commercial software for trigeneration problems such as Cycle Tempo, Linear programming (LP), Lagrangian Relaxation (LR)-Based Algorithm and matrices modeling are mainly focusing on the trigeneration system selection and optimization. However, these techniques are difficult to set up and master.

1.3 Problem Statement

Global climate change has raised public concern and focus towards the reducing energy consumption and as well as harmful environmental emissions. These issues have increased the need for energy-efficient systems. Process integration to reduce the consumption energy and to produce the cost-effective minimum resource utilization network becomes important. Integrating a trigeneration system to a process can further reduce the consumption of energy. A systematic numerical pinch analysis technique that can provide designers with a good visualisation tool is therefore required for process integration of a trigeneration system to help achieve energy savings.

The process integration problem is summarized as follows:

Given a set of thermal data consisting of hot and cold streams for a process; specified power as well as refrigeration requirements, the problem involves finding an optimal scheme for integrating a trigeneration system with a process. The Segregated Problem Table Algorithm (SePTA) has been developed to simultaneously perform energy targeting, pinch point determination and optimal integration of the trigeneration system with individual processes at specific temperatures and corresponding heat loads. Finally, the savings derived from the scheme generated using SePTA and the one generated using current approach for integration of heat engine and heat pump will be compared.

1.4 Objective

The objective of this research is

- to develop a new numerical pinch analysis tool called the Segregated Problem Table Algorithm (SePTA) for simultaneous energy targeting and optimal process integration.
- to apply the new technique to a trigeneration system.

1.5 Scope of Research

The scope of this work include:

1. Analysis of state-of-art technique for energy targeting based on numerical pinch analysis

   This involves analysis of the current approaches on their advantages and disadvantages as well as limitation. The research gap and potential area of improvement are highlighted.

2. Procedure development

   This involves the development of new systematic algebraic/numerical technique for simultanoues energy and pinch point targeting. With this new procedure, individual stream matching can be visualized. It can be used to pinpoint the exact process and utility stream matches on top of targeting the multiple utility loads and levels.

3. Procedure testing

   The new systematic design procedure proposed in this research will be applied to industry case study.

4. Analysis of the state-of-art technique for process integration with trigeneration

   It involves analysis of the previous work on process integration with trigeneration systems, their advantages, disadvantages, limitations and the research gaps.

5. Analysis of heat pumps and heat engines individually

   This involves individual integration of heat engines and heat pumps with palm oil process. This approach is used to compare the energy savings between the trigeneration system with the individual heat pumps and heat engines.

6. Development of a procedure for optimal integration of a process with a trigeneration system

   A new systematic integration technique between a process and a trigeneration systems is established. The segregated problem table analysis technique is used for the first time to perform energy targeting and simultaneously integrate a trigeneration system with a process to maximize heat recovery, cooling duty recovery as well as power generation .

1.6 Research Contributions

The main contribution of this research include:

1. A new technique for simultaneous targeting and design of integrated energy networks

A new numerical tool for simultaneous energy targeting called Segregated Problem Table Algorithm (SePTA), which is able to show heat cascade profile across temperature intervals for continuous individual hot and cold streams and perform SePTA heat allocation (*SHA*).

2. A tool within SePTA to pinpoint the exact process and utility stream matches on top of targeting the multiple utility loads and levels. Thus, heat engines and heat pumps position can be exactly pinpointed to process and utility streams.

3. Implementation of SePTA for the first time on a palm oil process that involves a trigeneration system with heating, power generation, and chiller systems.

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