MATHEMATICAL MODELLING OF SIMULTANEOUS WATER AND ENERGY MINIMISATION CONSIDERING WATER MANAGEMENT HIERARCHY OPTIONS

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I lovingly dedicate this dissertation to my lovely mother who gave me endless love, trust, constant encouragement and supported me in each step of the way wherever I needed. I also dedicate this work to my family and friends for their patience, support, love and prayers.

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ABSTRACT

Water and energy are closely interlinked together. The goal to reduce water and energy simultaneously has been a growing research. However, previous studies only consider maximising water reuse and, in some cases, also include water regeneration. This study aims to develop a mathematical model to design water and energy network that further reduces the water consumption, considering the whole water management hierarchy (WMH) schemes. This includes elimination, reduction, reuse, outsourcing and regeneration. Two steps solution is proposed, which involves solving two MINLP models. First, water and energy minimisation network considering WMH schemes and direct heat transfer is designed. The obtained network is then improved by inclusion of indirect heat integration to minimise the objective cost function. Two cases of thermal data extraction are studied for heat integration, Case A extracts individual streams based on supply and targeted temperature, whereas Case B extracts stream after mixer based on mixer temperature and targeted temperature. Streams which temperature load is satisfied in direct heat transfer were excluded for heat integration. The proposed method has been tested with literature case study. The implementation of all possible WMH scheme yields a lower freshwater consumption and wastewater generation. The model selected 35% and 15% of reduction for demand 3 and demand 1 respectively. Case A yields a lower total operating cost but slightly higher investment cost compared to Case B. Case B result in a simpler heat exchanger network, but degradation of the potential energy causes more heating and cooling. Case A is chosen as the optimal network and exhibits 13% reduction of the total cost compared to the literature case study.

ABSTRAK

Air dan tenaga saling berkait rapat. Penyelidikan dengan matlamat untuk mengurangkan penggunaan air dan tenaga pada masa yang sama semakin berkembang Namun, kajian sebelum ini hanya mempertimbangkan pemaksimuman penggunaan semula air dan dalam beberapa kes, juga pejanaanan semula air. Kajian ini bertujuan membina satu model matematik untuk mereka bentuk rangkaian air dan tenaga yang mengurangkan lagi penggunaan air, dengan mempertimbangkan keseluruhan skim hierarki pengurusan air (WMH). Ini termasuk penghapusan, pengurangan, penggunaan semula, penyumberan luar dan pertumbuhan semula.. Kaedah dua langkah penyelesaian dicadangkan dalam kajian ini dengan menyelesaikan dua model MINLP. Pertama, rangkaian pengagihan air dan haba melalui skim WMH dan pemindahan haba secara langusng direka. Rangkaian yang diperolehi kemudiannya ditambah baik dengan melakukan integrasi haba secara tidak langsung untuk mengurangkan fungsi objektif kos. Dua kes pengekstrakan data haba telah diuji, Kes A mengekstrak aliran indvidu berdasarkan suhu asal dan suhu sasaran, manakala Kes B mengekstrak aliran campuran berdasarkan suhu campuran dan suhu sasaran. Aliran yang telah menepati suhu sasaran tidak dimasukkan untuk integrasi haba. Kaedah yang dicadangkan telah diuji dengan menggunakan kes daripada kajian kesusasteraan.Pelaksanaan skim WMH telah mengggurangkan penggunaan air dan penjanaan sisa buangan Model ini telah memilih 35% dan 15% ke atas operasi 3 dan operasi 1. Kes A menghasilkan kos operasi yang lebih rendah tetapi kos pelaburan yang lebih tinggi sedikit berbanding Kes B. Kes B menghasilkan rangkaian pertukaran haba yang lebih mudah daripada Kes A , namun degradasi tenaga keupayaan menyebabkan lebih banyak pemanasan dan penyejukan diperlukan. Kes A dipilih sebagai rangkaian optimal dan menunjukkan 13% pengurangan jumlah kos berbanding jumlah kos daripada kajian.kesusteraan.

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LIST OF ABBREVIATIONS

BARON	-	Branch-and-Reduce Optimisation Navigator
BOD	-	Biological oxygen demand
CC	-	Composite curve
CEMWN	-	Cost effective minimum water network
COD	-	Chemical oxygen demand
D	-	Demand
DCS	-	Distributed control system
FW	-	Fresh water
GAMS	-	General algebraic modeling system
HEAT	-	Heat Allocation and Targeting
HEN	-	Heat exchanger network
HRAT	-	Heat recovery temperature approach
LP	-	Linear programming
LPT	-	Load problem table
MILP	-	Mixed integer linear programming
MINLP	-	Mixed integer non-linear programming
MHA	-	Maximum heat allocation
MODWN	-	Model optimal design water network
MP	-	Mathematical programming
MPTA	-	Modified problem table algorithm
MSA	-	Mass separating agent
MTB	-	Mass transfer based
MWN	-	Minimum water network
MWR	-	Maximum water recovery
NAD	-	Network Allocation Design

NLP - Non-linear programming
NMTB - Non-mass transfer based
PTA - Problem table algorithm
S - Source
SBB - Simple Brach & Bound
SDCC - Source and demand composite curve
SHARP - Systematic Hierarchical Approach for Resilient Process Screening
SMEC - Superimposed mass and energy curves
STEP - Stream temperature versus enthalpy plot
SWE - Simultaneous water energy
TDS - Total dissolved solid
TSS - Total suspended solid
WA N - Water allocation network
WAHEN - Water allocation heat exchanger network
WCA - water cascade analysis
WMH - Water management hierarchy
WPA - Water pinch analysis
WUTN - water usage and treatment network
WW - Waste water

LIST OF SYMBOLS

Fs_m - Maximum water flow for source m (kg/s)

Fd_n - Maximum water flow for demand n (kg/s)

Fh_i - Heat capacity flow rate of hot stream (kW/K)

Fc_j - Heat capacity flow rate of cold stream (kW/K)

$Fosmax_{os}$ - Maximum flow rate of outsourcing unit (kg/s)

Tfw - Fresh water temperature (°C)

Tww - Waste water temperature (°C)

$Ts_{m,t}$ - Temperature for source m (°C)

$Td_{n,t}$ - Targeted temperature for demand n (°C)

$Trg_{rg,t}$ - Temperature of regeneration unit (°C)

$Tos_{os,t}$ - Temperature of outsourcing unit (°C)

$thin_i$ - Temperature inlet of hot stream (°C)

$thout_i$ - Temperature outlet of hot stream (°C)

$tcin_j$ - Temperature inlet of cold stream (°C)

$tcout_j$ - Temperature outlet of cold stream (°C)

$thuin$ - Temperature inlet of hot utility (°C)

$thuout$ - Temperature outlet of hot utility (°C)

$tcuin$ - Temperature inlet of cold utility (°C)

$tcuout$ - Temperature outlet of cold utility (°C)

Cfw_c - Contaminant concentration of fresh water (ppm)

$Cd_{n,c}$ - Maximum contaminant concentration of demand n (ppm)

$Cs_{m,c}$ - Maximum contaminant concentration of source m (ppm)

$Cosmax_{os,c}$ - Maximum contaminant concentration of outsource (ppm)

$Crgo_{rg,c}$ - Maximum contaminant concentration of regeneration unit (ppm)

Cp - Heat capacity of stream (kJ/kg. K)

$\alpha_{n,re}$ - Percentage of water reduction for demand n %

hh_i - Heat transfer coefficient of hot stream (kW/m^2°C)

hc_j - Heat transfer coefficient of cold stream (kW/m^2°C)

hhu - Heat transfer coefficient of hot utility (kW/m^2°C)

hcu - Heat transfer coefficient of cold utility (kW/m^2°C)

$Cost_{FW}$ - Cost of fresh water $/Tonne

$Cost_{HU}$ - Cost of hot utility ($/kW)

$Cost_{CU}$ - Cost of cold utility ($/kW)

C_{HE} - Investment cost of a heat exchanger ($/yr)

C_A - Pre-exponent term for area cost ($/yr)

B - Exponent for area cost

$F_{m,n}$ - Water flowrate from source n to demand m (kg/s)

Ffw_n - Freshwater flowrate to demand n (kg/s)

Fww_m - Wastewater flowrate discharged from source m (kg/s)

$Fos_{os,n}$ - Outsource flow rate supplied to demand n (kg/s)

$Firg_{m,rg}$ - Regeneration unit flow rate from source n (kg/s)

$Frgj_{rg,n}$ - Regeneration unit flow rate supplied to demand n (kg/s)

$Fwwtotal$ - Total waste water (kg/s)

A_m - Adjusted flow rate of water source m (kg/s)

B_n - Adjusted flow rate of water demand n (kg/s)

$Fda1_{n,el}$ - Flow rate of demand n for elimination option (kg/s)

$Fda2_{n,re}$ - Flow rate of demand n for reduction option (kg/s)

$Fda3_{n,og}$ - Original flow rate of demand n (kg/s)

$Tmix_{n,t}$ - Temperature after mixer (°C)

$th_{i,k}$ - Temperature hot stream i at inlet step k

$th_{j,k}$ - Temperature cold stream j at inlet step k (°C)

$dt_{i,j,k}$ - Temperature difference between hot stream i and cold stream j at step k (°C)

$dtcu_{i,}$ - Temperature difference between hot stream i and cold utility at step k (°C)

$dthu_{j,}$ - Temperature difference between hot utility and cold stream j at step k (°C)

Qw_n - Amount of energy withdrawn from demand n (kW)

Qs_n - Amount of energy supplied to demand n (kW)
Qww - Amount of energy withdrawn from waste water (kW)
Qsw - Amount of energy supplied to waste water (kW)
$Qwrg_{rg}$ - Amount of energy withdrawn from regeneration unit (kW)
$Qsrg_{rg}$ - Amount of energy supplied to regeneration unit (kW)
q_{ijk} - Exchanged energy between hot stream i and cold stream j at step k (kW)
qc_i - Exchanged energy between hot stream i and cold utility (kW)
qh_j - Exchanged energy between hot utility and cold stream j (kW)
$Aijk$ - Area of heat exchanger between stream i and j (m2)
Ahu_j - Area of heat exchanger between hot utility and cold stream j (m^2)
Acu_i - Area of heat exchanger between hot stream j and cold utility (m^2)
$ICrg_{rg}$ - Investment cost of regeneration unit ($)
$ICos_{os}$ - Investment cost of outsourcing unit ($)
$ICel_{n,el}$ - Investment cost of elimination unit ($)
$ICre_{n,re}$ - Investment cost of reduction unit ($)
H - Annual operating hours (hr/yr)
f - Annual operating time ratio for utilities
af - Annualised factor
σn - Equipment unit of demand n
B - Exponent for regeneration flow rate
λ - Exponent for outsourcing flow rate
ϵn - Number of equipment of demand n
$CostRg$ - Capital cost for regeneration unit ($)
$CostOs$ - Capital cost for outsourcing unit ($)
$Costreuse$ - Capital cost for reuse ($)
$Costre$ - Capital cost for reduction ($)
$CostEl$ - Capital cost for elimination
TIC - Total investment cost ($/yr)
TOC - Total operating cost ($/yr)
TAC - Total annual cost ($/yr)

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CHAPTER 1

INTRODUCTION

This chapter provides the current perspective of the global water and energy issues, followed by problem background and problem statement. Next, objective and scope of the study are discussed to develop the methodology and technique for designing the water and energy network.

1.1 Global Water Issue

The inadequate supply of the available freshwater resources to satisfy the needs has been a concern for past decades, even more, upsetting in these recent years. Human consumes water for various activities such as cooking, cleaning, washing, etc. The municipal use only accounts for a small fraction of the global freshwater consumption. Agriculture and industrial consume around 69% and 19% of the world's fresh water as shown in Figure 1.1(AQUASTAT, 2014). Industrial use of water varies with countries' income. High income countries in Europe and Northern America use more than 45%, while middle and low-income countries in Asia, Africa and Southern America consume less than 10% (AQUASTAT, 2014)

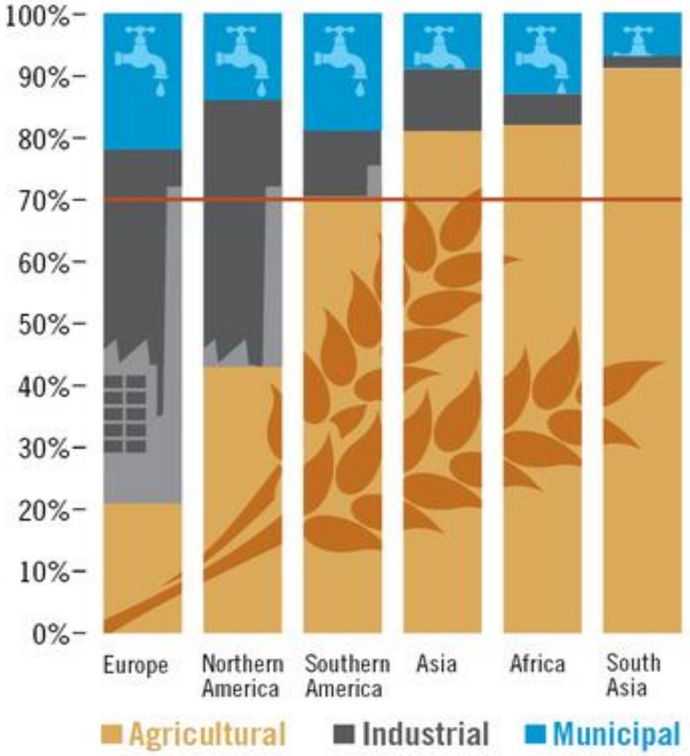

Figure 1.1 Global fresh water consumption (AQUASTAT, 2014)

The visible fresh water on the surfaces of rivers, lakes, and reservoir only represents a small part of the global freshwater resources. Figure 1.2 shows the fresh water's distribution on Earth. Almost two-third of the world's freshwater is stored in glaciers and ice caps, and only one-third of freshwater is available for human consumption (Gleick, 1996). The available fresh water is recycled through the hydrologic cycle, hence the absolute volume of the world's fresh water is relatively the same.

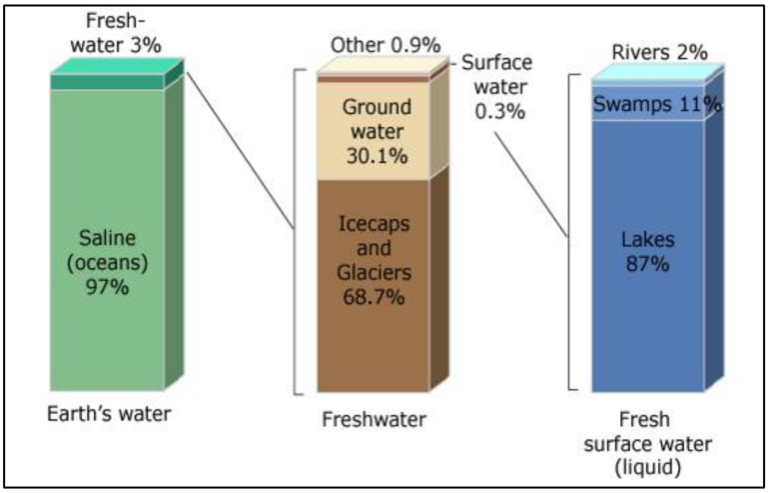

Figure 1.2 Distribution of Earth's water (Gleick, 1996)

While the supply of fresh water is limited, the water demand continues to increase rapidly. The world's population is continuously growing, and it is projected to expand to 9 billion people by 2050 (World Water Development, 2009). According to the United Nations, water use has grown at more than twice the rate of population increase in the last century and water withdrawals are predicted to increase by 50 percent by 2025 in developing countries, and 18 percent in developed countries (Global Environment Outlook, 2015).

The population growth is not the only factor to consider, the freshwater is withdrawn to meet the needs of different users. Industrial, urbanisation, irrigation for agriculture, and other sectors contribute a larger section of the world's fresh water consumption. These sectors are mounting and the competition for water is increasing. Water pollution from industrial wastewater and agriculture excess nutrients degraded the water quality result in less fresh water available for direct use.

Moderate water shortage was first recorded in the 18th century and it has increased with time and affected more people around the world in the years 1960 to 2005 mainly in Africa and Asia (Kummu *et al*,2010). Analysts estimate two-third of the human population will face water shortage by 2025 (United Nation, 2006). The water crisis is often associated with negative effects. People with limited access to clean freshwater usually faced inadequate sanitation which may lead to various health complications such as cholera, diarrhea, and dysentery.

Water is not distributed evenly over the glove, less than 10 countries possess 60% of the world's available fresh water supply (World Business Council for Sustainable Development, 2008). Many countries are sharing the same river basins, changes within a basin can lead to transboundary tensions. Water has been ranked as the top global risk in the World Economic Forum's 2015 Global Risks Report.

Water should be recognised as a great priority, correcting measures still can be taken to avoid the crisis to be worsening. There is an increasing awareness that our freshwater resources are limited and need to be protected both in terms of quantity and quality. Implementing water management for water-related activity is a good practise for decision-makers.

1.2 Global Energy Issue

Energy is important in today modern life. It powers the light and appliances at home, powers many industry processes and transportation. Figure 1.3 shows the world energy consumption for 2012. Approximately 52% of global energy is consumed for industrial activities while another 26% and 14% of global water are used for transportation and residential, respectively (EIA, 2012).

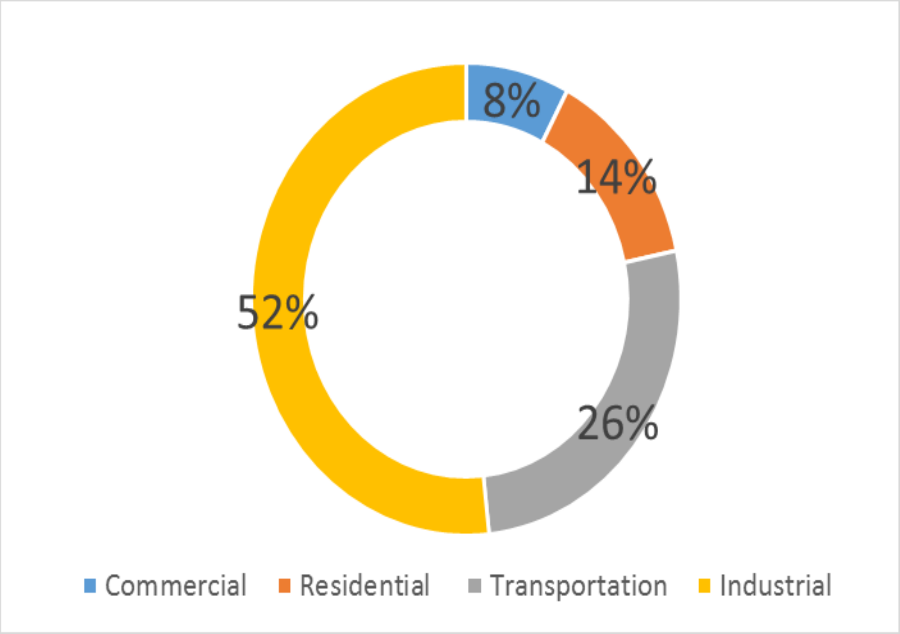

Figure 1.3 Global energy consumption by sector (EIA, 2012)

Fuel is required to generate energy, several fuel types include fossil (coal, oil, natural gas), nuclear, and renewable resource. Fossil fuels provide most of the energy in the world. Liquid fuels, natural gas, and coal account for 81% of total world energy consumption (EIA, 2014). Figure 1.4 shows the world energy supplies by fuels. Oil supplies the most with 31.3% followed by coal and natural gas with 28.6% and 21.2% respectively (EIA, 2014). These resources are finite and limited, and high consumption will lead to the depletion of non-renewable resources.

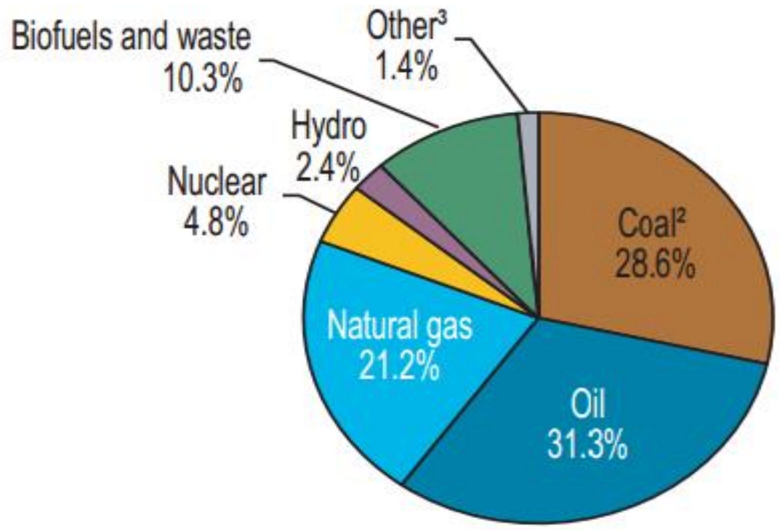

Figure 1.4 World energy supplies by fuel (EIA, 2014)

Economic growth in some regions especially Asia is projected to increase by 87% in 2040 as shown in Figure 1.5 (EIA, 2016). Energy demand increases as nations progress and living standards improve. More infrastructure, facilities, transportation are being built and the capacity to produce goods and services increase in fast-paced economic countries around the world. Population growth also drives for more transportation, houses, and businesses. Both factors are contributing to a higher global energy demand which put pressure on the global fossil fuel consumption.

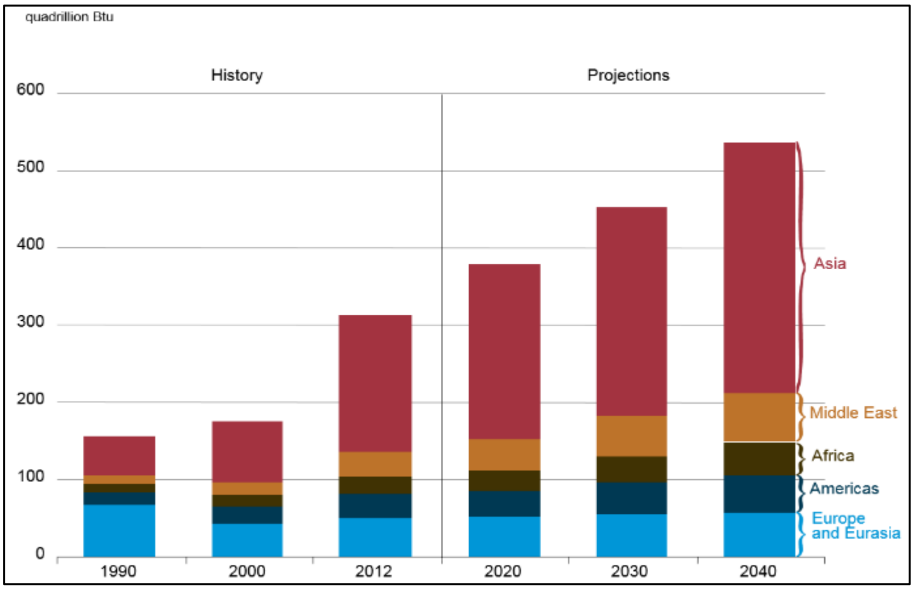

Figure 1.5 Energy consumption by region (EIA, 2016)

The main concern of many countries around the world is how to secure the resources for energy production to meet the user's needs. Energy is not only a matter of economic and financial but also affects the environment and social aspect. High environmental degradation is associated with the fossil fuel extraction activities. Emission of carbon dioxide into the Earth's atmosphere primarily from burning fossil fuels for energy is the main cause of the rising global temperature. The ideal goal is to protect the environment and having adequate energy supplies to meet the needs.

Much of the energy consumed in the world is wasted through transmission, heat loss and inefficient technology. Energy efficiency is an important tool to address the climate change and energy security. The main aim of energy efficiency is to reduce energy usage to provide the same amount of services and products. Energy efficiency also improves the competitiveness of businesses and reduces the dependence on foreign supplies for countries that import energy. Most of the countries share the common interest in improving energy efficiency performance.

1.3 Problem Background

Process industries consume a large amount of water for various activities in the process plant such as washing, cooling, separating, and etc. These activities require water with a certain quality at the specified temperature. Heating or cooling utilities are consumed to heat or cool the water to meet the operating condition. Most industries generate pollutants as by-products which contaminate the used water. Hence, pre-treatment is required to treat the water before discharge at end pipe.

Reduction of fresh water and energy is preferable in process plant mainly due to economic and environmental factors. Various studies have been conducted to minimise water (Liu *et al.*, 2008; Wan Alwi *et al.*, 2008; Deng *et al.*, 2011; Gadalla, 2015; Fan *et al.*, 2016; Li and Guan, 2016) or to minimise energy (Huang *et al.*, 2012; Gadalla, 2015; Chen *et al.*, 2015). These studies consider minimisation energy and water separately for many years. However, water and energy interact closely. For instance, some heat generated in water streams outlet may be used to heat another stream. These potential resources are often neglected and wasted.

The current drive towards environmental sustainability and the rising costs of fuel and water lead process industries to find new ways to reduce water and energy consumption. Freshwater and energy minimisation should be considered simultaneously since reducing fresh water usage leads to a lower energy consumption. Savelski and Bagajewicz (1997) first addressed simultaneous water and energy and later followed by Savulescu and Smith (2005a, 2005b), and many studies have emerged since then using graphical (Polley *et al.*, 2010; Leewongtanawit *et al.*, 2009; Hou *et al.*, 2014 and Xie *et al.*, 2016) or mathematical programming (Bogataj *et al.*, 2008; Dong *et al.*, 2008; Sahu *et al.*, 2010; Boix *et al.*, 2012; Ahmetovic *et al.*, 2013; Yan *et al.*, 2016 and Almaraz *et al.*, 2016).

Most of the simultaneous water and energy studies only focus on water reuse or water regeneration. Minimum freshwater usage is one of the main aims in the process plant which eventually result in lower utility consumption as well. Manan and Wan Alwi (2006) suggested the use of water management hierarchy (WMH) together with pinch analysis to achieve the minimum water target. WMH is is a hierarchy of water conservation priorities which consists of five different levels; namely: elimination, reduction, outsourcing/reuse ,regeneration and original. The most preferred option is elimination, followed by reduction of water demand. Next, direct reuse/recycling and water outsourcing through method such as rainwater harvesting are preferred. This is followed by regeneration or treatment of wastewater before being reused. Freshwater is the least preferred and will only be used when all water-saving options have been explored. This framework has successfully led to a significant water reduction. Hence, the aim of this study is to design an optimal water and energy network using WMH options and considering minimising total cost as the objective function.

1.4 Problem Statement

Given a set of temperature, flow rate, and contaminant concentration of global water operations, it is desired to develop a mathematical model to design a network that minimises fresh water usage, energy consumption, and total annual cost. The system will consider all water management hierarchy (WMH) options and direct-indirect heat transfer to achieve the objectives.

1.5 Objective

The main objective of this research is to develop a new mathematical model for designing a minimum water and energy network with minimum total annual cost. The system considers WMH schemes .The main objective is achieved by incorporating below objectives:-

1. To develop the mathematical model for maximising water recovery with minimum energy requirement based on available model in the literature
2. To extend the mathematical model by including other water management hierarchy options (Model 1); elimination, reduction, outsourcing and regeneration
3. To extend the mathematical model by including indirect heat integration; i.e, the usage of intermediate fluid to transfer heat between process streams, into the network to further reduce the energy consumption (Model 2)
4. To apply the mathematical model to the relative case study

1.6 Scopes of Work

There are six main scopes in this study:-

1. Reviewing the state of the art of simultaneous water and energy reduction using mathematical model and graphical approaches.
2. Developing the mathematical model for maximising water recovery with minimum energy requirement based on an available model in the literature.

3. Developing the mathematical model for minimising water and energy utilisation considering the whole water management hierarchy options – elimination, reduction, reuse, outsourcing, and regeneration (Model 1).

4. Developing the mathematical model to minimise the total annual cost correspond to heat integration (Model 2).

5. Applying the mathematical models on the relative literature case study.

6. Comparing the model results with literatures.

1.7 Overview

This thesis consists of six chapters. Chapter 1 provides an overview of the global water and energy issues, problem background, problem statement, objective and scope of the study.

Chapter 2 provides a review of the relevant literature for this study. The state-of-art review of the development in water and energy minimisation separately, as well as simultaneous water and energy are reviewed. Conceptual and mathematical programming techniques are also reviewed in this chapter.

Chapter 3 presents a general description of the proposed methodology of this study, whereas chapter 4 describes the detailed mathematical model construction. It consists of the water and energy network superstructure to achieve the minimum freshwater and utilities that correspond to the total annual cost, as well as the mathematical formulation derived from the superstructure.

Chapter 5 presents the results from the implementation of the developed methodology on the relative case study. The result is analysed and compared to determine the capability of the model on solving simultaneous water and energy problem Finally, Chapter 6 summarises the main points and includes recommendations to further improve this thesis

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