A MATHEMATICAL MODEL FOR WATER AND ENERGY NETWORKS

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A MATHEMATICAL MODEL FOR MINIMUM WATER AND ENERGY NETWORKS

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I lovingly dedicate this thesis to my parents who have always been my nearest and supported me in each step of the way wherever I needed them. I also dedicate this work to my sweet sister and brother, Elahe and Ali Reza.

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ABSTRACT

Mathematical programming is one the most used techniques in process integration, especially in water and energy network designs. Unlike conceptual and graphical approaches, mathematical programming is a better option in dealing with complex industrial water and energy systems, involving multiple contaminants and mass transfer based and non-mass transfer based operations. This thesis presents the development of a mathematical model for minimum water and energy networks considering direct heat transfer. The approach optimizes a superstructure which represents a set of all potential water minimisation arrangements together with direct heat transfer options and water and energy network configurations in a process system. The model has been set to minimize fresh water and energy consumption, cost applied to the system and wastewater discharged from the system. The model formulation is a mixed integer nonlinear program (MINLP) that is used to optimize an existing design. It considers all stages of water management hierarchy (i.e. elimination, reduction, reuse, outsourcing and regeneration) and operating cost factors simultaneously to bring about the lowest total cost. In this work fresh water contaminant concentration can be assumed as either zero or non-zero. The constraint for waste water temperature has been considered in the model. The model has been tested with a case study of a paper mill plant for retrofit case. The results show a minimization of 20.3% in annual operating costs which is roughly a 5 million dollar savings per year for the plant. The model showed that 97.96% reduction in wastewater generation and 60.2 % in utility consumption is achievable in compare with the previous graphical method. This shows that the model is very beneficial for the retrofit of industrial water and energy networks.

ABSTRAK

Pengaturcaraan matematik adalah salah satu teknik yang paling banyak digunakan dalam proses integrasi, terutamanya dalam reka bentuk rangkaian air dan tenaga. Berbeza dengan pendekatan konsep dan grafik, pengaturcaraan matematik adalah pilihan yang lebih baik dalam berurusan dengan system air dan haba industri yang kompleks dan, yang melibatkan pelbagai bahan cemar dan operasi berasaskan pemindahan jisim dan bukan berasaskan pemindahan jisim. Tesis ini membentangkan pembangunan model matematik untuk rangkaian minimum air dan tenaga mergambil kira pemindahan haba terus. Pendekatan ini mengoptimumkan superstruktur yang mewakili satu set bagi semua pengaturan pengurangan air yang berpotensi bersama-sama dengan pilihan pemindahan haba terus dan konfigurasi rangkaian air dan tenaga dalam sistem proses. Model ini telah ditetapkan untuk mengurangkan penggunaan air bersih dan.tenaga, kos yang digunakan untuk sistem dan air sisa yang dilepaskan dari sistem. Pembentukan model adalah program linear integer campuran (MINLP) yang digunakan untuk mengoptimumkan reka bentuk yang sedia ada. Ia mengambil kira semua peringkat hierarki pengurusan air (iaitu penghapusan, pengurangan, penggunaan semula, penyumberan luar dan perjanaan semula) dan kos operasi serentak untuk memperoleh jumlah kos terendah. Dalam kajian ini kepekatan pencemar air bersih boleh dianggap sebagai sama ada sifar atau bukan sifar. Kekangan untuk suhu air sisa telah diambil kira dalam model. Model ini telah diuji dengan satu kajian kes loji kilang kertas untuk kes retrofit. Keputusan menunjukkan pengurangan sebanyak 20.3% dalam kos operasi tahunan iaitu kira-kira satu 5 juta simpanan dolar setiap tahun untuk kilang. Model ini menunjukkan bahawa pengurangan 97,96% dalam penjanaan air kumbahan dan 60.2% dalam penggunaan utiliti boleh dicapai di bandingkan dengan kaedah graf sebelumnya. Ini menunjukkan bahawa model ini adalah sangat bermanfaat untuk retrofit rangkaian air dan tenaga industri.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

A_i - Adjusted flow rate of water source i

B_j - Adjusted flow rate of water demand j

$Cdmax_{j,k}$ - Maximum contaminant concentration of demand j

$Cirg_{i,rg}$ - Inlet concentration of contaminant k to reg unit rg

Cfw_k - Contaminant concentration of fresh water

Coldtariff - Cold utility cost

$Cos_{os,k}$ - Outsource concentration of contaminant k

Cp - Heat capacity of streams

$Cs_{i,k}^{max}$ - Maximum contaminant concentration of source i

$Crgo_{rg,k}$ - Outlet concentration of contaminant k from regeneration unit rg

$Da_{j,el}$ - Flow rate of demand j for elimination option el

$Da_{j,og}$ - Original water flow rate og for demand j

$Da_{j,re}$ - Flow rate of demand j for reduction option re

$Fdmax_j$ - Maximum flow rate for demand j

Ffw_j - Flow rate of fresh water to demand j

$F_{i,j}$ - Flow rate of water from source i to demand j

$Firg_{i,rg}$ - Water flow rate from source I to regeneration unit rg

$Fosmax_{os}$ - Maximum flow rate of outsource unit os

$Fos_{os,j}$ - Outsource flow rate os supplied to demand j

$Frgj_{rg,j}$ - Water flow rate from regeneration unit rg to demand j

$Fsmax_i$ - Maximum flow rate of source i

Fww_i - Flow rate of waste water discharge from source i

Hottariff - Hot utility cost

Qs_j - Amount of energy supplied per hour

Qtotal - Total energy supplied and withdrawn

Qw_j - Amount of energy withdrawn per hour
Qws - Amount of energy supplied waste waster
Qww - Amount of energy withdrawn from waste water
Tfw - Fresh water temperature
$Ti_{i,t}$ - Temperature for source i
$Tmix_j$ - Temperature after mixture
Tos - Temperature for outsourcing unit
Totalcost - Total cost of process
Trg - Temperature for regeneration unit
$Ttarget_{j,t}$ - Temperature of demand j
Tww - Waste water temperature
Wastetreatment - Waste water treatment cost
watertariff - Water price for industries
$X1_{j,el}$ - Selection of elth elimination option for jth demand
$X2_{j,re}$ - Selection of reth reduction options for jth demand
$X3_{j,og}$ - Selection of ogth reduction options for jth demand
$\delta_{j,re}$ - Percentage of water reduction re for demand j

Greek Letters

$\sum$ - Summation
$\forall$ - All belongs to

Subscripts

i - Index for water source
j - Index for water demand
k - Index for contaminant
t - Index for temperature

el	-	Index for elimination option
re	-	Index for reduction option
os	-	Index for outsourcing option
rg	-	Index for regeneration option
og	-	Index for original water demand

LIST OF ABBREVIATIONS

BARON - Branch-and-Reduce Optimization Navigator

BBC - British Broadcasting Company

MIWEN - Cost-Effective minimum water network

D - Demand

DCS - Distributed control system

FW - Fresh water

GAMS - General algebraic modelling system

HEN - Heat exchanger network

LNG - Liquefied Natural Gas

LP - Linear programming

MILP - Mixed integer linear programming

MINLP - Mixed integer non-linear programming

MPTA - Modified problem table algorithm

MSA - Mass separating agent

MTB - Mass transfer based

MWN - Minimum water network

MWR	-	Maximum water recovery
NLP	-	Non-linear programming
NMTB	-	Non-mass transfer based
OECD	-	Organization for Economic Co-operation and Development
OPEC	-	Organization of Petroleum Exporting Countries
S	-	Source
SDCC	-	Source and demand composite curve
UK	-	United Kingdom
WAHEN	-	Water allocation heat exchanger network
WMH	-	Water management hierarchy
WPA	-	Water pinch analysis
WW	-	Waste water

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter delivers an overview of the current world water and energy issues. Next parts come with problem background and problem statement. Then objective and scope of the study is discussed which involves the progress of a new methodology and technique to design water and energy networks based on mathematical programming and hierarchical approaches.

1.2 World Water Outlook

During the last decades, professionals have talk about the Earth's capability to sustain constantly growing human populations. It now appears that water will be one of the fundamental factors limiting forthcoming industries, agriculture and community areas. This inadequate supply is facing intense and unsustainable request from users of all kinds, and clients more and more have to compete for water with other sectors. Ecological uses of water, that may be the answer to guarantee the Earth’s water supply sustainability in the future, often get little notice.

World water possessions are passing through a phase of changeover. This changeover is, possibly, an outcome of express economic growth process, tied with other human activities in various parts of the globe. A world water disaster seems likely to emerge during the current century as demand for water is increasing at a quicker rate. In the 20th century, the world population became tripled while the resourced of renewable water has increased six-fold (Rosegrant et al., 2002). It is predicted that within the next fifty years, the world population will increase by another 40 to 50 %. This growth amount in population, beside industrial development and urbanization will cause a larger than ever claim for water and which will have strict influences on the environment (Rosegrant, et al., 2002).

An increase in fresh water consumption results in higher waste water production. There is further more waste water generation and spreading today compared to our planet history. About one human out of six require access to secure water for drinking, that is 1.1 billion people, and further than one out of three, don’t have access to adequate sanitation that is to say 2.6 billion people. As a result of water transmitted diseases, 3900 kids pass away every day (WHO and UNICEF, 2005).

As for global water consumption, agriculture consumes 70% of all water consumption, compared to 22% for manufacturing and 10% for urban use. In developed nations, however, industries consume more than half of the water existing for human use. Belgium, for instance, uses 80% of the available water for industry (World Water Council, 2010).

According to an article on BBC (Kirby, 2003), the water quantity on Earth is constant. From 1.4 billion cubic kilometres out of our planet, less than 0.01% of it is fresh water in lakes and rivers (Fig. 1.1).

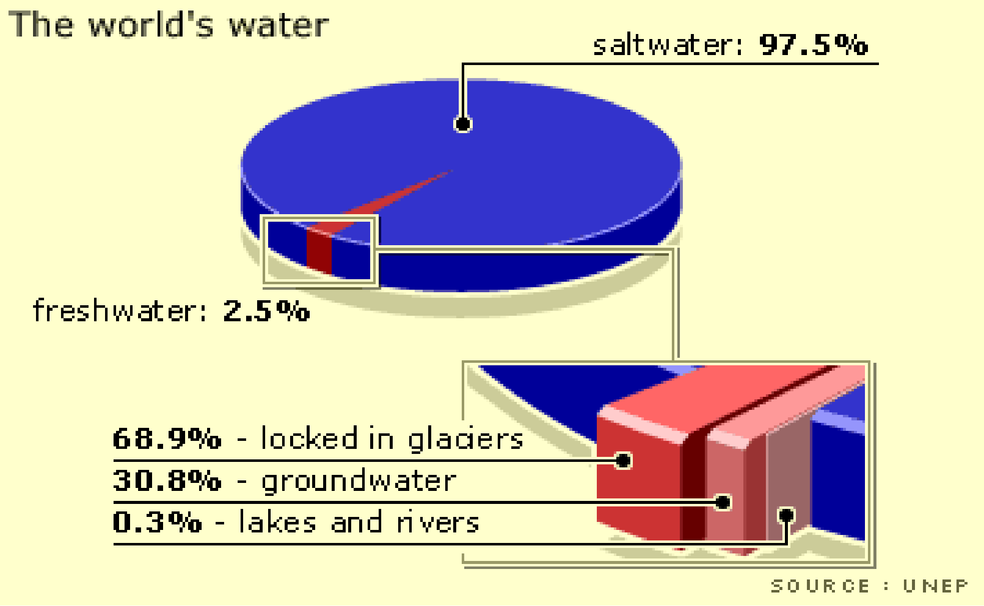

Figure 1.1: Earth's water sources (UNEP, 2006)

World water usage has increased by three times since 1950 and has been rising faster than the world's population. A large amount of the exploited fresh water becomes waste water (Fig. 1.2).

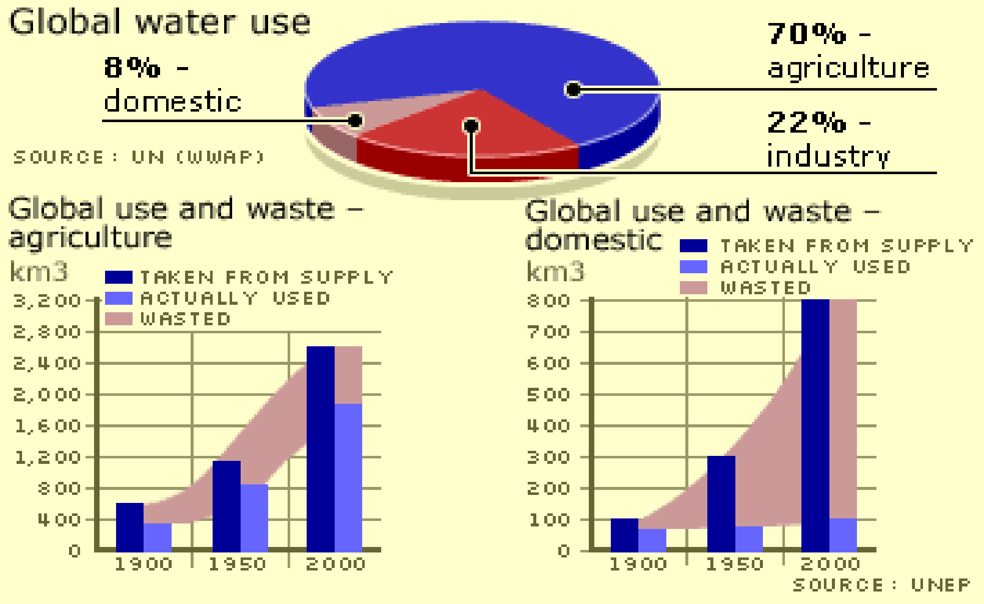

Figure 1.2: Earth's water sources (UNEP, 2006)

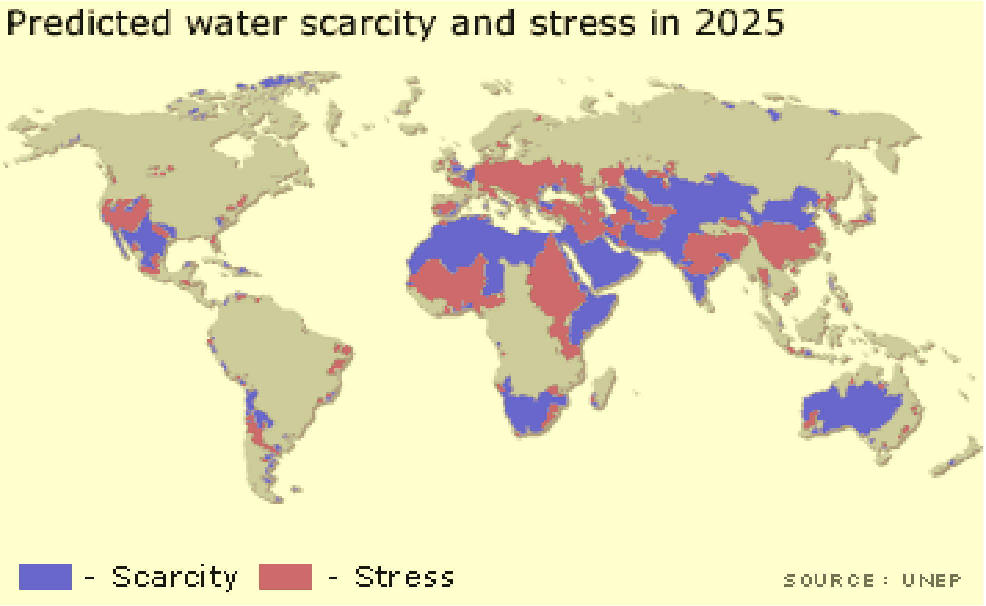

Figure 1.3: Water scarcity in 2025 (UNEP, 2006)

Asia and Africa are already facing water scarcity. Rising populations will impose more pressure in the approaching decades (Fig. 1.3).The important point here is that the world cannot add to its supply of fresh water. All it can do is changing the manner it uses it.

1.3 World Energy Outlook

According to British Petroleum statistical review of world energy (British Petroleum, 2011), world energy consumption in 2010 increased heavily, as a result of financial developments. The rise in energy utilization was multinational, with grown-up OECD which is the Organization for Economic Co-operation and Development, economies uniting in non-OECD countries is increasing at more than average speeds. With expansion in fossil fuels, all types of energy increased quickly, which resulted in such an increase in energy expenditure that made carbon dioxide emissions from energy use become at the greatest growing rate after 1969.

Energy price increases were diverse. For much of the year 2010, before going up in the fourth quarter, Oil prices stayed in a range of \$70-\$80.Typical oil costs for the whole year were the second-highest on record as the OPEC production cuts putted into action in 2008/09 which is still in place. As for the price of Natural Gas, it roared vigorously in the UK and in indexed markets' oil prices (as well as a great deal of the world's LNG).

World main energy expenditure that for the first time in 2010 includes renewable energies, increased by 5.6% in 2010, resulted in the highest increase (in percentage terms) after 1973. Energy expenditure in OECD countries amplified by 3.5% which is the highest expansion rate since 1984, while the level of OECD consumption leftovers around in line with that seen 10 years ago. Non-OECD consumption enlarged by 7.5% and was 63% higher than the year 2000 level. Consumption expansion amplified in 2010 for all regions, and increase was over average in all regions. Chinese energy consumption rose by 11.2%, and China left the US behind as the world's foremost energy consumer. Oil stays the world's most important fuel, at 33.6% of universal energy expenditure, but oil continued to lose market share for the 11th consecutive year (British Petroleum, 2011).

After declining for second consecutive year, global oil consumption increased by 2.7 million barrels per day(b/d), or 3.1%, to reach a record point of 87.4 million b/d. This was the highest percentage raise since 2004 but still the weakest global growth rate between fossil fuels. By an increase by 1.8 million b/d, or 2.2% in world oil production, it still did not go with the fast consumption growth. The most rapid increase since 1984 happened to world natural gas consumption by 7.4%. Except the Middle East, consumption growth was over average in all regions. The world's largest increase in consumption (volumetric) was for the US by rising 5.6% and to a new top record. The highest global growth since 2003 happened for coal consumption to be about 7.6% in 2010. Nowadays, coal is used to produce 29.6% of the global energy consumption, compared to 25.6% for ten years ago (British Petroleum, 2011).

The highest increase for world main energy expenditure since 1973take place in 2010 by an increase of 5.6%. growth was above average for oil, natural gas, coal, nuclear, hydroelectricity, as well as for renewable in power generation. Oil remains the dominant fuel (33.6% of the global total) but has lost share for 11 consecutive years (BritishPetroleum, 2011). The share of coal in total energy consumption continues to rise, and the share of natural gas was the maximum on record (Fig. 1.4).

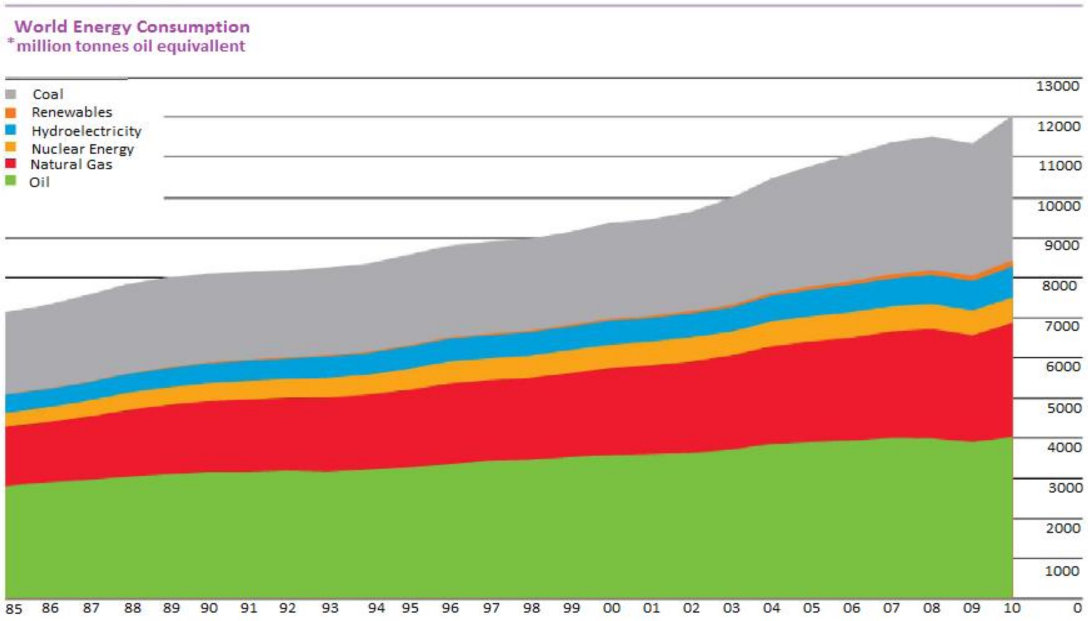

Figure 1.4: World Energy Consumption (1985-2010)

It is obvious that world energy consumption has been always increasing and in a close future when fossil fuels are going to be consumed, an energy crisis will occur. Global warming is another added problem which is today global issue. Since much of the produced energy is wasted, technologies which help to increase energy efficiency and energy conservation are vital. According to an article in NY Times, as an example 56% of all energy in the United States economy is wasted (Revkin, 2008) which the percentage for industrial and urban is 20% that makes developing new technologies to reduce and manage energy consumption an inevitable matter.

1.4 Problem Background

Among the process industries, water and energy are two main requirements. Substantial amounts of water require to be heated in some of them. As a result, in these types of processes, both the quality and temperature of the water are crucial. Accordingly, managing water and energy consumption have to be considered simultaneously.

Operations that water and energy are impacting each other or water systems which are heat-integrated, are very common chemical manufacturing plants. These types of plants consume energy which comes from fossil fuels and water for their operations. There is a call for efficient use of energy and water as a result of fresh water shortage, fast reduction of energy resources and harsher ecological laws. Diverse studies have been accomplished in order to reduce water and energy which is consumed in chemical manufacturing plants throughout the past three decades. These studies mostly are concentrating on either minimization of energy (Morar and Agachi, 2010) or minimization of fresh water requirements (Alva-Argáez et al., 2007; Bagajewicz et al., 2000; Bandyopadhyay, 2006; Takama et al., 1980). These studies paved the way for competent design of heat exchanger networks (HENs) and water allocation networks (WANs). Nonetheless, it is vital to remind that in a chemical manufacturing plant with heat-integrated water systems, water and energy are closely related and dependent to each other. It is found that the minimization of manufacturing fresh water expenditure consequences in both the minimization of wastewater generation and reduction in the crucial energy requirements for heating and cooling processes. Accordingly, energy and water management matters in process plants need to be noticed simultaneously, rather than separately.

To achieve the optimal water and energy network design separately and simultaneously, different kinds of approaches has been tested by scientists. Among these, two methods are the most practiced ones which are graphical methods and mathematical methods. Heuristics and graphical methods (Bandyopadhyay, 2006; Dunn and Wenzel, 2001; El-Halwagi et al., 2003; Hallale, 2002; Manan et al., 2009; Wan Alwi and Manan, 2008, 2010; Wan Alwi et al., 2008) which are based on thermodynamic rooted concept of pinch technology, at first has been introduced for heat integration purposes and then developed and has been used in water minimization and other materials e.g. hydrogen and carbon. Graphical approaches are quick, interactive and easy to understand methods, but they become tedious and less accurate in large scale and complex processes. In the other hand, mathematical models (Bagajewicz, et al., 2000; Bagajewicz and Savelski, 2001; Papalexandri and Pistikopoulos, 1993; Teles et al., 2008) are more accurate and comprehensive for using with large scale processes. Cost effectiveness of the water and/or energy networks design has been discussed in several works (Ahmad et al., 1990; Gundepsen and Naess, 1988; Linnhoff and Ahmad, 1990; López-Maldonado et al., 2011; Wan Alwi, 2007; Wan Alwi and Manan, 2006). Simultaneous optimal water and energy network design has also been studied here and there in recent years especially in the last three years (Dong et al., 2008; Feng et al., 2009; George et al., 2011; Ismail et al., 2011; Jian et al., 2003; Leewongwanawit et al., 2004; Manan, et al., 2009; Polley et al., 2010; Savulescu et al., 2005a, 2005b; Wan Alwi and Manan, 2010). The research gap which remains here that is the aim of this study is developing a new model which uses cost factors and heuristics to design optimal simultaneous minimum water and energy networks.

1.5 Problem Statement

Given a series of water using processes which have different temperature constraints for various sources and demands, it is desired to design a network which minimizes the use of fresh water, waste water, energy and cost. The system will, consider all of the water management hierarchy options and non-isothermal heat transfer to meet the aforesaid objectives using mathematical programming.

1.6 Objective of the Study

The main objective of this study is to develop a new mathematical model to design a water and energy network which simultaneously minimizes the fresh water and energy utilization, waste water generation and utility cost to the system using mathematical programming approach considering water management hierarchy and direct heat transfer.

1.7 Scope of the study

To achieve the objective, some major milestones have been defined in this study. The scope of this study is inclusive of:

1. Reviewing state-of-the-art techniques on simultaneous water and energy network design which include mathematical and heuristic approaches.

2. Performing an optimization model on water-energy systems that considers Water Management Hierarchy options and non-isothermal mixing to attain the minimum heat integrated water network resulting in minimum operating cost for the system.

4. Applying the optimization model on case studies to check the accuracy and effectiveness of the approach.

1.8 Research Contributions

The key specific contributions of this work are summarized as follows:

1. A new optimization model for synthesis of minimum water and energy networks for multiple contaminant problems and indirect heat transfer.

The model has been developed to obtain minimum water and energy utilization network that considers all process change options in WMH (i.e. elimination, reduction, reuse/recycle, outsourcing and regeneration) and non-isothermal heat transfer simultaneously.

2. The model can be employed to the cases with pure fresh waters and multi contaminant streams.
3. The model can be applied to different urban and industrial sectors since it is capable of solving systems with mass transfer based (MTB) and non-mass transfer based (NMTB) streams.

1.9 Overview

This thesis is inclusive of four chapters. Chapter 1 reveals an overview of the global water and energy issues, problem background, problem statement, objective and scope of the study.

Chapter 2 gives the fundamental theory behind water, waste water and energy minimization.

Chapter 3 gives a review on literatures relevant to the subject of this study. The development of the science on water and energy network design techniques using pinch technology, heuristic approaches and mathematical programming are reviewed.

Chapter 4 describes the methodology of the research to achieve defined objectives.

Chapter 5 is about the results achieved and a discussion about them.

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