OPTIMAL DESIGN OF WATER NETWORK WITH IMPOVED OPERABILITY

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OPTIMAL DESIGN OF WATER RECOVERY NETWORK WITH IMPROVED OPERABILITY

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ABSTRACT

A suitable water network for any water using process can help reduce the amount of fresh water usage. Many researchers have investigated water recovery network for multiple contaminants using mathematical programming. However, operability problems and complex network design have made the actual implementation of the design impractical. In this research, a MINLP mathematical model to design new water recovery network with improved operability is presented. The method considers tanks for intermittent streams based on capacity, omitting small flow rates, preferring more economical streams for cost minimization purposes piping reduction. The approach has been successfully implemented for both industrial and urban cases. CCM Chemicals has been chosen for industrial case study and Sultan Ismail Mosque in UTM as an urban case study. The result shows 17.6% saving on freshwater usage and 53.8% reduction of wastewater generation in CCM Chemicals, giving an approximate saving of RM 34,942 per year on freshwater consumption. Moreover, 3 tanks have been considered in water system and 18 reuse streams have been removed for simplification of water network. This resulted in reduction of piping requirement for water reuse. For SIM case study, freshwater consumption is reduced by 14.56% wastewater generation is reduced by 22.9%. It gives a monetary saving of RM 1,250 per year on freshwater cost. In addition, 2 tanks for intermittent streams are considered and 3 small streams are deleted from the water network. This elimination caused reduction of piping requirement for water network.

ABSTRAK

Satu air sesuai rangkaian untuk sebarang air menggunakan proses dapat menolong mengurangkan jumlah penggunaan air tawar. Banyak penyelidik menyiasat rangkaian pemulihan air untuk bahan-bahan cemar berbilang menggunakan pengaturcaraan matematik. Halangan di jaringan pemulihan air seperti masalah-masalah operability, pengawal kompleks reka bentuk , dan sistem perpaipan kompleks membuat pelaksanaan sebenar reka bentuk tidak praktis. Dalam penyelidikan ini, satu pemulihan air baru reka bentuk rangkaian dan pengawal telah disampaikan. Dalam pendekatan ini, dengan penurunan gangguan-gangguan pengawal dengan pemudahan rangkaian air, mempertimbangkan air kelabu (GW) menggunakan semula, mempertimbangkan sistem penuaian air hujan untuk rangkaian air, satu rangkaian pemulihan air dan pengawal yang mana lebih sesuai dan praktikal telah direkabentuk. Pendekatan telah berjaya dilaksanakan untuk kedua-dua kes-kes perindustrian dan bandar. Ccm Chemicals telah dipilih untuk kajian kes perindustrian dan Sultan Ismail Mosque di UTM sebagai satu kajian kes bandar. Keputusan menunjukkan 17.6% menjimatkan penggunaan air tawar dan 53.8% pengurangan generasi air buangan di CCM Chemicals, memberi satu simpanan kasar RM 34942 setiap tahun di penggunaan air tawar. Juga , kerana kajian kes MSI pengurangan 14.56% di penggunaan air tawar dan 22.9% di generasi air buangan. Keputusan memberi RM 1250 setiap tahun di kos air tawar di kajian kes MSI. Model menunjukkan pengurangan di penggunaan air tawar dan generasi air buangan, kurang masalah gangguan dan operability di reka bentuk pengawal, pertimbangan GW dan sistem-sistem penuaian air hujan di kedua-dua kajian kes perindustrian dan bandar.

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LIST OF ABBREVIATIONS

AOT	-	Annual operating hours of the operation
$Cd_{j,k}$	-	Contaminations of demand
Cf_k	-	Contaminations of freshwater
Chemicalfee	-	Chemical for regeneration unit
Costoffresh	-	Overall cost of freshwater
Costofreuse	-	Overall cost of reuse
$Cs_{i,k}$	-	Contaminations of sources
Ct_k	-	Contaminations of treatment facility output
$CV^{10\%\ Increase}$		10% Increase in control variable
D_j	-	Water demands
$\frac{dCV}{dMV}$		Gradient of control variable over manipulated variable
$Disfx_{f,j}$	-	Distance between fresh water source f and demand j in x direction
$Disfy_{f,j}$	-	Distance between fresh water source f and demand j in y direction
$Disfz_{f,j}$	-	Distance between fresh water source f and demand j in z direction
$Distx_{i,t}$	-	Distance between water source i and treatment facility t in x direction
$Disty_{i,t}$	-	Distance between water source i and treatment facility t in y direction
$Distz_{i,t}$	-	Distance between water source i and treatment facility t in z direction

$Disttx_{t,j}$	-	Distance between treatment facility t and water demands j in x direction
$Distty_{t,j}$	-	Distance between treatment facility t and water demands j in y direction
$Disttz_{t,j}$	-	Distance between treatment facility t and water demands j in z direction
$Disx_{i,j}$	-	Distance between source i and demand j in x direction
$Disy_{i,j}$	-	Distance between source i and demand j in y direction
$Disz_{i,j}$	-	Distance between source i and demand j in z direction
$Fl_{i,j}$	-	Flow rate from source i to demand j
Ftot	-	Total freshwater usage
FTT_j	-	Streams from regeneration unit to water demands
FW_j	-	Freshwater Streams to demands
Fwcost	-	Cost of fresh water supply
Fwcostt1	-	Overall freshwater cost
$Fwstreamprice_j$	-	Price of stream from freshwater to each demand
L_j	-	Reuse selection based on complexity
Maintenance	-	Maintenance cost of Regeneration
$Massload_{j,k}$	-	Mass load difference between input and output streams of each process
$MV^{10\%\ Increase}$		10% Increase in manipulative variable
Pipeprice	-	Price of pipe in RM per meter
Pricefreshpiping	-	Piping price from freshwater to demands
Priceoverall1	-	Freshwater and reuse cost
Priceoverall2	-	Overall cost of the system
Pricepiping	-	Piping price between sources and demands
PY	-	Payback period

Regenpipe	-	Overall piping cost for regeneration unit
Regenunitcost	-	Cost of Regeneration unit
Regppcost	-	Cost of water pumps
Regucost	-	Cost of regeneration unit
$Reuse_{i,j}$	-	Allowable reuse streams
S_i	-	Water sources
$S1_{i,j}$	-	Reuse Selection based on cost
Staffcost	-	Salary of staff per year
Staffnum	-	Number of staff required
$Streamprice1_j$	-	Each stream price from source i to demand j
$Tank_{i,tr}$	-	Number of tanks required for water demands j
Tankbase	-	Excess cost of higher capacity tanks
Tankcost	-	Overall tank cost
Tankprice	-	Price of tanks in RM per unit
Totalreuse	-	Total water reused
Totreuse	-	Amount of water reused
Totreuse2	-	Overall allowable reuse
W_i	-	Waste stream going from sources to regeneration unit
Wcost	-	Cost of waste treatment for discharge
Z	-	Cost exponential factor

LIST OF GREEK LETTERS

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

LIST OF SUBSCRIPTS

i	-	Index for water source
j	-	Index for water demand
f	-	Index for fresh water source
t	-	Index for treatment facility
k	-	Index for contamination
tr	-	Index for required tanks in the system

LIST OF ACRONYMS

BARON	-	Branch-and-reduce optimization navigator
BOD	-	Biological oxygen demand
CV	-	Control variable
DO	-	Dissolved oxygen
EC	-	Electrical conductivity
GAMS	-	Generalized algebraic modeling programming
GW	-	Greywater
HN	-	Hardness
LC	-	Level controller
LP	-	Linear programming
LT	-	Level Transmitter
MILP	-	Mixed integer linear programming
MINLP	-	Mixed integer non linear programming
MTB	-	Mass transfer based
MV	-	Manipulative variable
NLP	-	Non linear programming
NMTB	-	Non mass transfer based
PPM	-	Part per million
PSO	-	Particle swan optimization
RBC	-	Rotating biological contractor
RM	-	Ringgit Malaysia
SBR	-	Sequencing batch reactor

SIM	-	Sultan Ismail Mosque
TDS	-	Total dissolved solids
UTM	-	Universiti Teknologi Malaysia
WPA	-	Water Pinch Analysis

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Chapter 1

Introduction

1.1 Introduction

This chapter gives an overview on the current water situation globally. The global need for water saving and the methods to solve this issue is presented in Section 1.1 and 1.2. The research background of this work discussed Section 1.3. Then the problem statement and the objective of this research are presented in Sections 1.4 and 1.5. Section 1.6 gives a brief description of the whole thesis.

1.2 Water Global Overview

Water is one of the most valuable resources available to mankind (Mazur, 1998). Nowadays, water usage around the world can be approximately divided into three main categories, agriculture, industrial and residential usage (see Figure 1.1). Internal water footprint is the volume of water used from domestic water resources and the external water footprint is the volume of water used in other countries to produce goods and services which is consumed by the inhabitants of the country (Hoekstra and Chapagain, 2007).

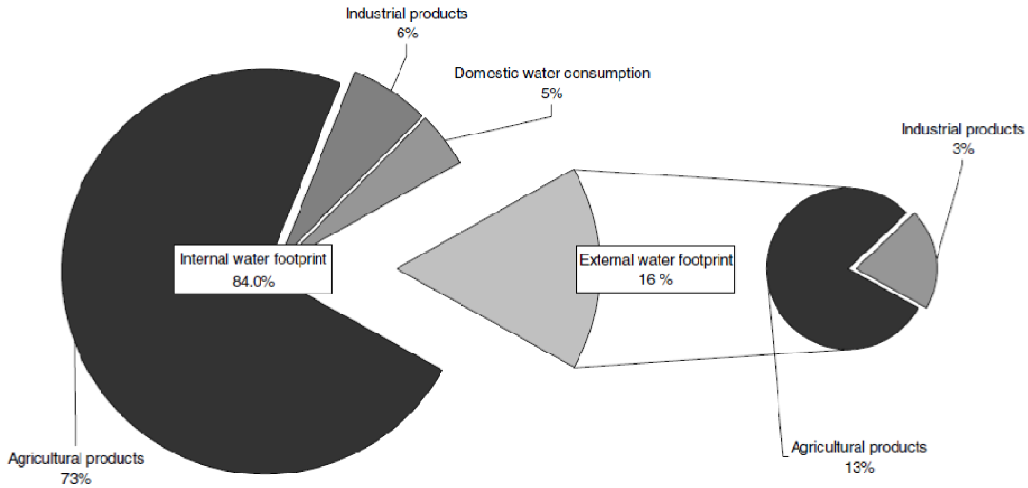

Figure 1.1: Global water consumption (Hoekstra and Chapagain, 2007)

Statistics show that 97% of the water on the Earth is salt water (Mazur, 1998). And only 3% percent is fresh water. From this 3% of fresh water, over two third of this amount is frozen in glaciers and polar ice caps. Mazur (1998) claimed that the remaining unfrozen fresh water that includes the amount that is useful for human usage is mainly available as groundwater. Only a small portion present is above ground as surface water or in the air. On the other hand, growing populations, changing diets, increased urban, agricultural and industrial water demands, and a growing understanding of nature's need for water require that we reform our attitude toward water usage and the way it is managed globally (Falkenmark, 1990). Water needs to be on the global political agenda not only in order to feed the projected 9 billion people that will inhabit the earth by 2050 with less agricultural water than is available today, but also in order to address the critical development challenge of doing so in a safe, sustainable way without compromising water resources that are essential to ecosystem services and functions. Awareness of the global importance of preserving water for ecosystem services has just recently emerged, during the 20th century, when more than half the world's wetlands have been lost due to misuse along with their valuable environmental services.

While Europe is by large considered as having the adequate water resources, water scarcity and drought is an increasingly frequent and widespread phenomenon in the European Union. The long-term imbalance resulting from water demand exceeding available water resources is no longer uncommon (Oki and Kanae, 2006). It was estimated that by 2007,at least 11% of Europe’s population and 17% of its territory had been affected by water shortage.

The Arab world, one of the driest regions on the planet, will tip into severe water scarcity as early as 2015(Vörösmarty et al., 2010). Until then, Arab countries will be forced to survive on less than 500 cubic meters of fresh water per year each, or even below one tenth of world’s average of more than 6,000 cubic meters per capita, according to the report by the Arab Forum for Environment and Development.

Considering the impact that water deficiency may have on human life, it is crucial to decrease the amount of water usage in industries and urban environments. In recent years, scientists had come up with several solutions to face water scarcity. Water recovery and water reuse /recycle is proved to be one of the important aspects of the solution(Vörösmarty et al., 2000).Considering this, a beneficial method to save water is application of Water Pinch Analysis in industry and urban environments. This technique reduces the amount of fresh water usage in the system, which result in decrease in wastewater generation and treatment investment that ultimately leads todecrease in capital cost.

1.3 Overview on Water Pinch Analysis

1.3.1 Water Pinch Analysis

In the recent years, governments' attitude toward environmental impacts of industries has been changing. They have established new legislations regarding reduction of industrial waste and enforce industries to comply. Today, reducing industrial waste has become one of the major obstacles in industries because water is one of the major industry wastes. The ability to recover wastewater through reuse or other methods can be a very important step.

Water Pinch is a systematic technique to analyze water networks and identify different possibilities to more efficient use of water in industry processes (Ulson de Souza et al., 2011). The main focus of WPA is the reduction of flow to the wastewater treatment unit. In other words, WPA tries to reduce the amount of fresh water used and wastewater generated in the plant. In the new plants, WPA should be a normal part in design and it should be treated as a normal design procedure. Water Pinch is applicable to any industry, which consumes fresh water and generates wastewater in any way. It is also applicable to even most complex industrial sectors. It is certain that the amount of savings achieved by applying WPA is very reliant on project objectives. Solutions that will be identified after the application of WPA often can do much more than saving fresh water. It will usually reduce capital investment and recover raw materials etc.

1.4 Problem Background

The fresh water supply industry is vitally important not only to maintain the health of the community, but for the sustainability of industry, business and agriculture. The volumes of water consumed each day by agriculture, industry and the public are vast. Water usages in industries constitute amajor part of global water usage since industries are very reliant on water for all levels of production. In industries, water can be used as a raw material, solvent, coolant, transport agent, and energy source. This means that water must be protected, conserved, and used in a proper manner. In order to be able to save water in chemical plants, water integration technique has been presented by many recent researches in order to target and design the minimum water usage or the maximum amount of water recovery.

An obstacle that has not been considered previously is that although this approach gives the maximum amount of water recovery, the design and implementation is questionable. In other words, there are other aspects that needed to be considered in a maximum water recovery network design for industries or buildings.Several research questions remain such as:

1. Is the current water recovery network design proposed by the previous researchers practical in term of actual implementation?

2. What are the factors that need to be considered in order to ensure a successful water recovery system design?

3. Is it possible to consider operability problems in water recovery network design in order to design an implementablewater system?

4. What is the cost trade off between the amount of water savings and the increase of complexity of multi contaminant system?

1.5 Problem Statement

Water recovery networks have been designed with the objective of achieving the maximum water recovery by minimizing the amount of fresh water usage and wastewater generation.This objective commonly leads to a very sophisticated model with complex piping system and high implementation cost. In order to make the model more practical, the most practical way to this obstacle is to design a water network by taking into account the operability problems. The result will be an optimal integrated plant and with less operability problems, which can be an important step.

1.6 Objective of this study

The main objective of this research is to design a maximum water recovery network system by taking into account the operability problems. This method would result in a suitable water recovery networkwith less operability problems.

1.7 Scope of Work

To achieve the objective of the research, these four key tasks should be identified. The scope of this study includes:

1. Analyzing the operability problems and limitations
2. Consideration of rainwater harvesting and grey water reuse limitations and possibilities.
3. Designing a water recovery network model through mathematical programming
4. Applying the model to urban and industrial case studies.

1.8 Summary of the Thesis

This thesis consists of five chapters. Chapter 1 gives an overview of the global and water issues. It also consist a review on water integration technique. It follows by describing the problem background, problem statement and the objective of this research, which aims to develop systematic approach for designing a suitable maximum water recovery network and controller for water network involving multiple contaminants using mathematical programming approach.

Chapter 2 provides a review of the relevant literatures presented in this thesis. This includes a review on WPA. It also gives a brief review on water integration and fundamental controller design and mathematical programming.

Chapter 3 presents the mathematical model for improved controllability minimum water network design.

Chapter 4 presents the results on implementing the developed methodology on industrial and urban case studies to demonstrate the applicability of the mathematical model.

Lastly, Chapter 5 summaries the main points and contributions of the thesis and gives a perspective for future works.

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