UNIVERSITI PUTRA MALAYSIA

A FRAMEWORK FOR ESTABLISHING INDUSTRIAL EFFLUENT LIMITS WITH APPLICATION TO THE IRON AND STEEL INDUSTRY IN IRAN

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By

MARYAM MAHJOURI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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DEDICATION

This thesis is dedicated to the memory of my late father, Ali Ashraf Mahjouri, for his passion for knowledge.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

A FRAMEWORK FOR ESTABLISHING INDUSTRIAL EFFLUENT LIMITS WITH APPLICATION TO THE IRON AND STEEL INDUSTRY IN IRAN

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December 2017

Chairman: Associate Professor Mohd. Bakri Bin Ishak, PhD
Faculty: Environmental Studies

The establishment of Emission Limit Values (ELVs), especially in the industrial sector, is one of the most problematic environmental issues in developing countries. In addition, industrial effluent limitations should be established regarding the special characteristics of each sector. In Iran, with a uniform "Wastewater Effluent Standard", a scientific methodology for determining ELVs at the sector level is an essential need. The objective of this study is to present a reliable and pragmatic methodology for establishing ELV thresholds at the sector level with an emphasis on the Best Available Technology (BAT) concept. In general, the most common approach for technology evaluation and ELVs identification, in both developed and developing countries, is expert judgment. Therefore, this research employs a multi-dimensional approach. A hybrid Fuzzy multiple-criteria decision-making (FMCDM), consisting of the Analytic Hierarchy Process (AHP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) in combination with fuzzy logic is structured to make use of the combined benefits of several methods. The modelling framework includes three main sections that is: a) determining the most appropriate Wastewater Treatment Technologies (WTTs); b) computing the emission levels associated with the Best Practicable Control Technology Currently Available (BPT) concept; and c) identifying the final ELVs based on the results of the two previous sections. Iran's iron and steel industry, which constitutes a fundamental sector in the country's economy, is selected as the case study. The results obtained indicate that experts have considered the country-specific information, which consists of the most appropriate WTTs and ELVs related to BPT, as a reliable reference in their decisions. According to the findings, corrective measures in accordance with the BAT considerations should be implemented in many of the plants under consideration and the experts largely prefer the more advanced WTTs, because of their high system efficiency and compatibility with environmental impact criteria. This transparent stepwise process has resulted in defensible country-specific ELVs for the iron and steel industry, which can be developed for other sectors. As the main conclusion, this study demonstrates that FMCDM is a systematic and robust operational decision tool for this comprehensive

assessment regarding the data availability limitations in developing countries and emphasises industrial sustainability. This hybrid model of AHP, TOPSIS and Fuzzy logic offers better results and provides a higher degree of confidence for this sophisticated judgment. It is a multi-dimensional approach that considers the sector characteristics; the interaction of the technical, environmental and economic aspects; and the specific preferences in developing countries.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

RANGKA KERJA UNTUK MENETAPKAN HAD EFFLUEN INDUSTRI DENGAN APLIKASI DALAM INDUSTRI BESI DAN KELULI DI IRAN

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Pembentukan Emission Limit Values (ELVs), terutama dalam sektor industri, merupakan salah satu isu persekitaran yang paling bermasalah dalam negara membangun. Sebagai tambahan, had efluen perindustrian seharusnya ditubuhkan meliputi ciri-ciri khusus setiap sektor. Di Iran, “Wastewater Effluent Standard”, satu metodologi saintifik untuk menentukan ELVs pada sesuatu sektor merupakan satu keperluan yang penting. Objektif kajian ini adalah untuk menunjukkan metodologi yang boleh dipercayai dan pragmatik dalam menubuhkan ambang ELVS dalam peringkat sektor yang menekankan konsep Best Available Technology (BAT). Secara umum, pendekatan yang lazim digunakan dalam penilaian teknologi dan pengenalpastian ELVs, dalam negara maju dan membangun adalah penilaian pakar. Oleh itu, kajian ini menggunakan pendekatan multi-dimensi. Pembuat keputusan hibrid kabur pelbagai kriteria, meliputi proses Analytic Hierarchy Process (AHP) dan Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) dengan kombinasi bersama logik kabur telah distrukturkan dengan menggunakan faedah gabungan beberapa kaedah. Rangka kerja permodelan meliputi 3 seksyen utama iaitu a) menentukan Wastewater Treatment Technology (WTTs) yang paling berkesan, b) pengiraan tahap pelepasan berhubung dengan konsep Best Practicable Control Technology (BPT) dan c) mengenal pasti ELV terakhir berdasarkan hasil dua seksyen sebelumnya. Industry besi dan keluli di Iran, yang mana meliputi sektor asas dalam ekonomi negara seperti yang dipilih oleh kajian kes. Keputusan yang diperolehi menunjukkan para pakar telah mengambil kira maklumat spesifik negara, yang mana mengandungi WTTs dan ELVs yang paling bersesuaian dengan BPT, yang merupakan rujukan yang boleh dipercayai dalam keputusan mereka. Berdasarkan kepada penemuan kajian, langkah-langkah pembetulan yang sesuai dengan pertimbangan BAT harus dilaksanakan pada tanaman-tanaman yang dipertimbangkan dan para pakar lebih memilih WTTs yang lebih maju, kerana kecekapan yang tinggi dan kesesuaian sistem mereka dengan kriteria impak alam sekitar. Proses langkah bijak yang telus ini telah menyebabkan ELVs bagi negara khusus untuk industri besi dan keluli tidak dapat dipertahankan, yang mana ia boleh dibangunkan untuk sektor lain. Sebagai

kesimpulan utama, kajian ini menunjukkan bahawa FMCDM adalah alat untuk membuat keputusan operasi yang sistematik dan mantap untuk penilaian komprehensif mengenai keterbatasan ketersediaan data di negara-negara membangun dan menekankan kemampanan industri. Model hibrid AHP, TOPSIS dan Fuzzy Logic ini menawarkan hasil yang lebih baik dan memberikan keyakinan yang lebih tinggi untuk penghakiman yang canggih ini. Ini adalah pendekatan pelbagai dimensi yang mempertimbangkan ciri-ciri sektor; interaksi teknikal, aspek alam sekitar dan ekonomi serta keutamaan tertentu di negara membangun.

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I certify that a Thesis Examination Committee has met on 5 December 2017 to conduct the final examination of Maryam Mahjouri on her thesis entitled "A Framework for Establishing Industrial Effluent Limits with Application to the Iron and Steel Industry in Iran" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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LIST OF ABBREVIATIONS

AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
BAT	Best Available Technology
BATNEEC	Best Available Technology Not Entailing Excessive Cost
BCT	Best Conventional Pollutant Control Technology
BOD_5	Biochemical Oxygen Demand
BPT	Best Practicable Control Technology Currently Available
BPT-AELs	BPT - Associated Emission Levels
BREFs	Best Available Technology Reference documents
CC	Closeness Coefficient
Cd	Cadmium
CI	Consistency Index
CN	Cyanide
COD	Chemical Oxygen Demand
COV	Coefficient Of Variation
Cr	Chromium
CR	Consistency Ratio
Cu	Copper
CVI	Content Validity Index
CWA	Clean Water Act
DL	Detection Limit
DMs	Decision - Makers
DOE	Department of Environment
DR	Direct Reduction

DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
ELVs	Emission Limit Values
EQO	Environmental Quality Objective
EQSs	Environmental Quality Standards
EU	European Union
F	Fluoride
FAHP	Fuzzy AHP
FCC	Fuzzy Closeness Coefficient
FDM	Fuzzy Delphi Method
Fe	Iron
FMCDM	Fuzzy multiple-criteria decision-making
FNIS	Fuzzy Negative Ideal Solution
FPIS	Fuzzy Positive Ideal Solution
Hg	Mercury
HSE	Health, Safety and Environment
GOF	Goodness-of-Fit
GRA	Grey Relational Analysis
IPPC	Integrated Pollution Prevention and Control
ISESs	Industry - Specific Effluent Standards
K-M	Kaplan-Meier
MCDM	Multi-Criteria Decision-Making
MHME	Ministry of Health and Medical Education
MLE	Maximum Likelihood Estimation
MOA	Ministry of Jahad-e-Agriculture

MOE	Ministry of Energy
NAFTA	North American Free Trade Agreement
ND	Non-Detect
Ni	Nickel
NIS	Negative Ideal Solution
NPDES	National Pollution Discharge Elimination System
NSPS	New Source Performance Standards
Pb	Lead
PIS	Positive Ideal Solution
PROMETHEE	Preference Ranking Organization Method for Enrichment of Evaluations
PSES	Pretreatment Standards for Existing Sources
PSNS	Pretreatment Standards for New Sources
RCI	Random Consistency Index
ROS	Regression on Ordered Statistics
TBELs	Technology-Based Effluent Limitations
TFN	Triangular Fuzzy Number
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TSS	Total Suspended Solid
T-W	Tarone-Ware
UCL	Upper Confidence Level
USEPA	USA Environmental Protection Agency
VFs	Variability Factors
VIKOR	Multi criteria Optimization and Compromise Solution (A Serbian word)
WAD	Water Affairs Department

WEPA	Water Environment Partnership in Asia
WFD	Water Framework Directive
WMW	Wilcoxon-Mann-Whitney
WQBELs	Water Quality-Based Effluent Limitations
WTTs	Wastewater Treatment Technologies
Zn	Zinc

CHAPTER 1

INTRODUCTION

1.1 Background

In most developing countries, the improvement of environmental policy is a crucial issue. Environmental problems are linked with social and economic aspects which must be considered in the development of any environmental program or regulation (Gumus, 2009). According to the Europe 2020 Strategy (European Commission, 2010), the promotion of greener, more competitive and more efficient economy is a priority in sustainable growth (Giner-Santonja et al., 2012). In general, water plays a key role in the long term national sustainable development. The growing water demands, decreasing water availability and increasing water pollution highlight the extreme importance of an integrated effective water and wastewater management. However, sustainability concerns consider environmental aspects in a more integrated outlook (Alley and Leake, 2004). Water impacts on all three development aspects consisting of social, economic and environmental. To enhance the efficiency of water management, the related policies should be planned in conjunction with all these aspects. To attain the progressive water resources management, each country needs to identify its priority actions. In a realistic approach, all the challenges have to be addressed with respect to the local perspectives, cooperation of decision-makers from different sectors and participation of all related stakeholders.

The control of pollution sources, consisting pollution prevention and reduction, is considered to be one of the cornerstones for sustainable water management. Industrial wastewater is one of the most vital contributors to environmental pollution. Each year, an estimated 300-400 million tons of wastes consisting: heavy metals, solvents, toxic sludge and etc. are discharged by industries (UN-Water, 2011).

Unfortunately, in Iran, during previous decades, unsustainable industrial development has resulted in the water resources pollution. According to the report of “Water Comprehensive Plan”, in 2002, industrial water demand and the produced wastewater were 1079 and 579 million m^3, respectively. In 2012, less than 30% of this industrial wastewater had efficient WTTs (Tajrishy, 2010). It is predicted, in 2022, industrial water demand and the resulted wastewater would be 2101 and 1088 million m^3, respectively (Iranian Ministry of Energy, 2010).

The effective wastewater regulations are essential in environmental protection. The direct regulation (command and control) is one of the main subdivisions of the environmental regulation and it includes specific standards such as mandatory limitations and prohibitions which forces companies to adapt to new environmental changes and then checks their compliance with regulations (Camison, 2010) through inspections and controls (Testa et al., 2014). Such regulations are performed through defining, applying and enforcing effluent standards for waste water discharges

(Konterman et al., 2003; Ragas et al., 2005). In most ~~of~~ countries, water-related legal instruments have already been established. In many developing countries, there is an identified need to improve the existing laws and regulations to make their implementation strong and effective. It highlights the necessity of a targeted, transparent and rational standards supported by compliance and enforcement. Therefore, the procedure of establishing and implementing effluent standards is an essential pre-requisite in solving water pollution problem (Ragas et al., 2005) and a dynamic and pragmatic standard should consider different environmental, technical, institutional and economic dimensions in the country.

1.2 Problem statement

There is no doubt about the fact of serious water crisis in Iran (Madani, 2014). Now, Iran faces water scarcity, as a critical national security issue (Future Directions, 2014), and in 2035 will be faced with water stress (Poorasghar and Mohammadnejad, 2007). Regarding the ratio of total withdrawals to total renewable supply, Iran is considered as an extremely high stress country (World Resources Institute, 2013). Long- term water and wastewater mismanagement and thirst for development are among the main reasons for current situation (Madani, 2014).

There are many challenges in dealing with industrial wastewater (Tajrishy, 2010). The rapid industrialization has resulted in an increasing proportion of industrial water consumption and wastewater production in the country (National Research Council, 2005), which plays a critical role in threatening of the existing water resources (Tamaab Organization, 2004). Therefore, a significant water reform is required in Iran and water and wastewater management should shift from crisis management to preventive management which benefits from non-structural measures such as regulations, monitoring and controlling (Madani, 2014). Now, “Wastewater Effluent Standard” is applied as the main standard for water pollution control in the country (DOE, 1999). In this standard which has been compiled by Department of Environment (DOE), effluents discharged from different sources should be in accordance with the standards defined for: surface water, absorbents wells, and water used for agriculture and irrigation (DOE, 1999). Although “Wastewater Effluent Standard” is the main applied standard in the country, in recent years, a new standard as well as a new criterion respectively known as “Environmental Criteria of Treated Wastewater and Return Flow Reuse” and “Effluent Standards for Municipal Wastewater” have been established (Iranian Ministry of Energy, 2010). In general, in Iran, the agriculture sector consumes the highest water quantity. Regarding the government’s policies in optimizing the water resources allocation among different sectors in the future, the focus of the above-mentioned standard and criterion is on treating and reusing of municipal and agricultural effluents for agricultural lands (Iranian Ministry of Energy, 2013).

However, among different water pollution sources, the special attention should be paid to industrial effluents. Regarding the crucial role of environmental pollution deriving from industrial activities (Kunz et al., 2013; Tseng et al., 2013; Test et al., 2014), industry-specific effluent standards (ISESs) are applied in most countries. In Iran, the uniform "Wastewater Effluent Standard" which is employed throughout the country has not considered any specific industrial effluent limitations. Consequently, there is a need to focus on transforming the uniform effluent standard to the ISESs with special emphasis on categorical effluent standard, as a vital step in controlling the pollution sources. Generally, the uniform limitations among different sectors cannot reflect the differences in their processes, treatment technologies and management abilities (Kim et al., 2014).This need is highlighted especially for the most fundamental and strategic industries, "oil and gas" and "Iron and Steel", in the country (Karbasian, 2014; World Bank Group, 2017; The Iran Projects, 2017; Organization for Investment Economic and Technical Assistance of Iran, 2017). In 2005, Iranian Ministry of Petroleum prepared "Engineering Standard for Water Pollution Control". However, no specific effluent standard has been established for Iron and Steel industry yet. Therefore, a practical and transparent method for establishing the specific categorical effluent standards has to be developed in a stepwise procedure.

Moreover, the effluent standards need to be reviewed and, if appropriate, revised regularly to achieve a practical and dynamic control with respect to the continuously changing situations and priorities (Kim et al., 2010). In fact, industrial development has resulted in new pollutants. With the advancement of analytical tools, monitoring of contaminant levels in the environment has been improved and following the fate of ecosystems after pollution has been more precisely (Leith et al., 2010). It seems the range of control is being greatly increased by rising in the number of pollutants and decreasing in the level of allowable concentration (Kim et al., 2010). In Iran, the effluent standard should have been revised, at least, every three years while it was amended more than 20 years ago (Iranian Ministry of Energy, 2013). The revision of effluent standard is one of the most important priorities in improving management of water resources in Iran. In this effluent standard, the included pollutants have to be reviewed and, if there is a need, the new pollutants in receiving environments have to be selectively involved, gradually. Therefore, a well-structured, pragmatic and reproducible methodology is a specific need towards determining reliable ELVs.

It is crucial to emphasize the fact that ELVs depend on contextual criteria and the development of reliable ELVs requires many considerations. In addition to the specific technical characteristics of each industry, ELVs have to be adapted to other aspects, such as the geographical location, the local environmental conditions (Lopez-Gamero et al., 2009; Testa et al., 2014), the economic viability and institutional infrastructure of the country. In fact, copying standards from the others, especially developed countries, results in ELVs which are impractical and inefficient. Regarding the significant differences between developed and developing countries in their capabilities, especially their data availability, even an identical method for effluent standard setting cannot be proposed. Furthermore, few methods for deriving ELVs have been described in the literature. For example, in the European Integrated Pollution Prevention and Control (IPPC) directives and documents, only a few methodologies correspond exactly to the IPPC requirements (Laforest, 2014) and no details are provided concerning how the emission data analysis should be done to select the ELVs (Carretero et al., 2016).

This study proposes a stepwise contextual decision-making process as a scientific and practical guidance for establishment of ELVs for industrial sector. For the first time, this new adapted approach considers the economic feasibility, technical practicability and institutional capability (Ragas et al., 2005) of the country.

1.3 Scope of the study

In order to take measures which can improve the water quality in the most efficient way and develop a scientific strategy, it is necessary to set priorities. Regarding the importance of industrial effluents in the pollution of environment, and the lack of its related standards in Iran, this research is focused on the industrial effluents.
In the process of establishing efficient and defensible ELVs, the special attention should be paid to the industrial categorization. In this study, the Iron and Steel industry, as one of the most strategic sectors in the country (Karbasian M., 2014; The Iran Projects, 2017; Organization for Investment Economic and Technical Assistance of Iran, 2017), was selected for performing the methodology. The fundamental role of this sector in Iran's economy along with its increasing growth highlight the need for its country-specific effluent standard. However, in the future, the proposed method may be developed among other categories of industries in the country in a stepwise manner by DOE. Consequently, the main scope of this research is the industrial effluents with emphasis on application in Iran's Iron and Steel sector. Since the process of ELVs determination relies in a large extent on expert judgment (Polders et al., 2012), this research introduces a robust operational decision-making framework for using the best professional judgment of experts and incorporating large amounts of well-structured information. Different Multiple-criteria decision-making (MCDM) techniques are employed to present an integrated picture for the establishment of ELVs.

1.4 Research objectives

The main objective of this research is to develop a framework for determining national effluent ELVs in a specific sector through a transparent, systematic, and reproducible way. This can result in a rational and scientific approach for industrial effluent standard setting in the country. This research was designed to attain the following specific objectives:

1. To examine and identify Best Practicable Control Technology Currently Available (BPT) for "Iron and Steel Industry" and to estimate its related ELVs,
2. To identify the key evaluation criteria and indicators for sustainable reducing of the industrial wastewater pollution and to determine the optimal WTTs which indicates the capability of plants in pollution reduction and compliance with ELVs,
3. To propose country – specific ELVs for the selected industry according to the experts' opinions by comparing different ELVs and considering the capabilities and limitations of Iran as a developing country.

1.5 Significance of the study

In countries experiencing high environmental pressure and water resources scarcity, employing an effective pollution control system is vital. An example of such a country is Iran, which is located in an arid and semi-arid area. In Iran, the average annual rainfall, about 250mm, is almost one third of the average world precipitation. Additionally, seasonal and local rainfall distribution in Iran varies considerably, from 50mm in the eastern and central deserts to more than 2,000mm in the northern area. Consequently, Iran presently faces water scarcity, and, by 2035, is predicted to face water stress (Poorasghar and Mohammadnejad, 2007). Furthermore, rapid population growth and the increasing trend in industrial and agricultural development have resulted in increasing water demand and producing a huge amount of municipal, industrial and agricultural effluents that are threatening the quality of the water resources. Therefore, the promotion of modern water and wastewater management approaches is very critical in the country. Since the scientific and pragmatic environmental regulations can efficiently reduce pollution, developing an adapted approach of standard setting with respect to the country-specific capacities and constraints, must be considered as a fundamental necessity.

The findings of this research can be applied as a reference for Iran's Iron and Steel industry in: selecting the optimal WTTs with emphasis on industrial sustainability, proposing defensible country-specific ELVs in line with BAT concept and even improving other sound emission reduction strategies, such as standards and regulatory compliances.

In addition, other industries can apply this approach in their decision-making process with respect to their differences in capacities, limitations, wastewater characteristics and local conditions. This approach can be employed from the level of individual plants to local or national measures. Its flexible and transparent framework provides the opportunity to employ in other developing countries.

In brief, the methodology presents a reliable and practical stepwise process at the sector level, which can be developed for other industries, especially in the context of developing countries with their technical, economic and institutional constraints, mainly the data availability limitations.

1.6 Limitation of the study

Since the purpose of this research is establishing the ELVs in a contextual process regarding local environmental, economic, technical, social and institutional considerations, the methodology should be developed on the basis of the actual technological set-up and the prevailing conditions in the country.

The quality and quantity of data and information play a vital role in determining reliable ELVs. The experience indicates that industries are not willing to provide their related emission data and background information and often consider them as their sensitive and confidential data. In fact, the availability of these data is a possible bottleneck in employing the methodology. Although, in Iran, the DOE follows up the environmental performance of plants and has identified specific laboratories for periodically sampling and analysing the effluent of the plants, the detailed background information can only be provided by the plants. The accurate emission data and background information cannot be provided from all plants of the sector under consideration.

In this research, complementary information was gathered from a variety of sources, such as: Iranian Mine and Mining Industries Development and Renovation Organization, Iranian Steel Producers Association, National Iranian Steel Company, and interviews with experts within this sector. On the other hand, with respect to the prevailing structure of this sector in the country, the best representative installations were identified and the study focused on providing their accurate and detailed emission data and background information.

1.7 Thesis organization

The body of this thesis is ordered as below:
Chapter 1 focuses on the general background of the water resources management in relation to the pollution control, the statement of the problem and the scope, objectives, importance and constraints of this study.

Following this introduction, Chapter 2 reviews the relevant literature on environmental regulations and standards with emphasis on industrial effluents. It describes the main approaches of effluent standard establishing and compares different countries' performances in this context. Regarding the study area, the characteristics of water and wastewater in Iran are presented and then related standards, criteria and guidelines are mentioned. In this chapter, a thorough review on Iron and Steel industry, as the selected sector, is conducted. And finally, the expert judgment methods are introduced for this multidimensional study.

In Chapter 3, the main flowchart of research methodology is illustrated. This chapter explains data collection process, applied statistical techniques and the procedure of each applied decision making method in details. It also introduces the special software used for censored data analysis.

Chapter 4 presents the obtained results answering the defined objectives. In this chapter, different decision making methods are applied and compared to illustrate their strengths and weaknesses. It comprises numerous tables and figures for better understanding of the research findings.

Chapter 5 provides the overall research conclusions and recommendations to improve and expand this study.

Finally, the samples of used questionnaires and supplementary tables, graphs and computations as well as the software results are attached as appendices.

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