

## TABLE OF CONTENTS

Original Literary Work Declaration	ii
Abstract	iii
Abstrak	iv
Acknowledgements	v
Table of Contents	vi
List of Figures	ix
List of Tables	x
List of Abbreviations	xi
<b>CHAPTER 1 - INTRODUCTION</b>	
1.1 Environmental Performance Measurement	1
1.2 Motivation	6
1.3 Aims and Objectives of the Study	8
1.4 Research Questions	8
1.5 Thesis Structure	9
<b>CHAPTER 2 - REVIEW OF LITERATURE</b>	
2.1 Introduction	11
2.2 Concept of Efficiency	12
2.3 Traditional Efficiency Measurement Approaches	13
2.4 Production Frontiers Approach	14
2.4.1 Parametric Frontier Approach	15
a) Parametric Deterministic Frontiers	15
b) Parametric Stochastic Frontiers	15
2.4.2 Non-Parametric Frontier Approach	17
a) Non-Parametric Deterministic Frontiers	17
b) Non-Parametric Stochastic Frontiers	18
2.5 Data Envelopment Analysis (DEA)	18
2.6 Undesirable Factors in DEA	20
2.7 Various approaches in DEA with undesirable output	22
2.7.1 Indirect approach	23
2.7.2 Direct approach	26
a) Hyperbolic Efficiency (HE) model	26
b) Directional Distance Function (DDF) model	27
c) Slack Based Measure (SBM) model	28
d) Additive model	29
e) Range Adjusted Measure (RAM) model	30
f) Alternative models	32
2.8 Concept and Measurement of Productivity Change	34
2.9 Empirical Orientation	35
2.9.1 Technical efficiency and productivity change in manufacturing sector	36
2.9.2 Eco-efficiency analysis in the manufacturing sector	39
2.9.3 The application of various approaches in different levels of study	42
2.9.4 The effect of environmental regulation on the environmental efficiency	44
2.9.5 Potential variables and sources of pollution by different industry	46
2.9.6 Productivity growth and environmental performance in the Malaysian manufacturing context	48
2.10 Conclusion	53

<b>CHAPTER 3 - THE METHOD OF DEA, DDF AND MLPI</b>		
3.1	Introduction	55
3.2	Production Possibility Set (PPS)	56
3.3	Data Envelopment Analysis (DEA)	58
	3.3.1 DEA Fractional Program	59
	3.3.2 Fractional Program to Linear Program	60
	3.3.3 CCR and BCC Models	61
	3.3.4 A slack-based measure in DEA	68
3.4	Model incorporating the desirable and undesirable outputs	70
3.5	Directional Distance Function (DDF)	74
3.6	Malmquist Luenberger Productivity Index (MLPI)	79
3.7	Conclusion	85
<b>CHAPTER 4 - THE DEVELOPMENT OF THE SDDF APPROACH</b>		
4.1	Introduction	87
4.2	Directional Slack-based Distance Function (DSDF)	88
4.3	Super DSDF Eco-efficiency (SDEE)	96
4.4	Malmquist Luenberger Productivity Index (MLPI)	105
4.5	Specification on Variables Selection	111
	4.5.1 Determination of Decision Making Unit (DMU)	111
	4.5.2 Determination of Input and Output Variables	113
	4.5.3 Data Source	115
4.6	Conclusion	120
<b>CHAPTER 5 - RESULTS AND DISCUSSIONS</b>		
5.1	Introduction	122
5.2	Efficiency Analysis using the DEA and DDF Approaches	123
	5.2.1 Technical Efficiency	124
	5.2.2 Eco-Efficiency	132
5.3	Efficiency Analysis using the SDDF Approach	142
	5.3.1 New Eco-Efficiency	142
	5.3.2 Scale Direction and Target Value	146
	5.3.3 Super DSDF Eco-Efficiency (SDEE)	151
5.4	Productivity Change using the Malmquist Luenberger Productivity Index (MLPI)	153
5.5	Conclusion	162
<b>CHAPTER 6 - CONCLUSIONS AND RECOMMENDATIONS</b>		
6.1	Research Summary	165
6.2	Discussions on Major Empirical Findings	167
6.3	Research Contributions of the Study	171
6.4	Policy and Managerial Implications	173
	6.4.1 Firm Level in the Manufacturing Sector	173
	6.4.2 Industry Level in the Manufacturing Sector	176
	6.4.3 State Level in the Manufacturing Sector	177
6.5	Limitations	178
6.6	Recommendations and Future Research Direction	179

<b>REFERENCES</b>	181
<b>APPENDIX A</b>	201
<b>APPENDIX B</b>	209
<b>APPENDIX C</b>	217
<b>PUBLICATIONS</b>	225

## LIST OF FIGURES

Figure 2.1	Production Frontiers	18
Figure 3.1	Production Possibility Set	57
Figure 3.2	CRS and VRS technology frontier	62
Figure 3.3	The efficiency frontier for output oriented DEA model	67
Figure 3.4	Illustration of the SBM model	70
Figure 3.5	A graphical representation for environmental production function	74
Figure 3.6	The efficiency frontier for DDF model	76
Figure 3.7	Malmquist Luenberger productivity indicator	81
Figure 3.8	Infeasible problem with mix period in MLPI	84
Figure 4.1	DDF and DSDF direction vector	95
Figure 4.2	Super-efficiency frontier	98
Figure 4.3	Eco-efficiency frontier and super efficiency frontier for DMU B, C and D	101
Figure 4.4	Infeasibility problem in super-efficiency model	103
Figure 4.5	Reference frontier using a three-year window of data	108
Figure 5.1	Shifts in technical efficiency scores for the states under the FIZ category	128
Figure 5.2	The trend of technical efficiency scores for FIZ, N-FIZ and total geometric mean	131
Figure 5.3	Malaysia's growth rates of key sectors from 1971 to 2010	131
Figure 5.4	Shifts in eco-efficiency scores for the states under FIZ category	136
Figure 5.5	The trend of DDF eco-efficiency scores for FIZ, N-FIZ and total geometric mean	138
Figure 5.6	A comparison between CO <sub>2</sub> emission and eco-efficiency score	139
Figure 5.7	The trend between DDF eco-efficiency and DEA technical efficiency score	140
Figure 5.8	Shifts in DSDF eco-efficiency scores for the states under the FIZ category	144
Figure 5.9	The trend of DSDF eco-efficiency scores for FIZ, N-FIZ and total geometric mean	145
Figure 5.10	The difference in eco-efficiency scores between the DDF and DSDF approach	145
Figure 5.11	Actual and target value for sales and CO <sub>2</sub> for 2001	148
Figure 5.12	Actual and target value for sales and CO <sub>2</sub> for 2010	150
Figure 5.13	The trend for productivity change from 2003 to 2010	156
Figure 5.14	The trend for eco-efficiency change from 2003 to 2010	158
Figure 5.15	The trend for technological change from 2003 to 2010	160
Figure 5.16	The trend for the MLPI and its component from 2003 to 2010	161

## LIST OF TABLES

Table 2.1	Empirical studies on efficiency measurement of manufacturing sector in Malaysia	49
Table 3.1	CCR models with input and output orientation	64
Table 3.2	BCC models with input and output orientation	65
Table 4.1	Numerical example of DDF and SDDF	94
Table 4.2	Numerical example of super-efficiency	101
Table 4.3	Lists of DMUs	111
Table 4.4	Categories of FIZ and N-FIZ states	112
Table 4.5	List of variables	115
Table 4.6	Descriptive statistics of the data set for 15 states from 2001 to 2010	117
Table 4.7	Results of correlation analysis from 2001 to 2010	119
Table 5.1	Results of the DEA technical efficiency score and rank from 2001 to 2010	127
Table 5.2	Results of the DDF eco-efficiency score and rank from 2001 to 2010	135
Table 5.3	The DDF eco-efficiency results determined by the different direction vector	141
Table 5.4	Results of the DSDF eco-efficiency score and rank from 2001 to 2010	143
Table 5.5	Results of scale direction, target value and change for the inefficient state for 2001	147
Table 5.6	Results of scale direction, target value and change for the inefficient state for 2010	149
Table 5.7	Results of super SDDF eco-efficiency score and rank from 2001 to 2010	152
Table 5.8	Productivity change using the MLPI calculated by DDF from 2001 to 2010	154
Table 5.9	Productivity change using the MLPI calculated by DSDF from 2003 to 2010	155
Table 5.10	Eco-efficiency change using the MLPI calculated by DSDF from 2003 to 2010	157
Table 5.11	Technological change using the MLPI calculated by DSDF from 2003 to 2010	159

## LIST OF ABBREVIATIONS

APO	Asian Productivity Organization
BCC	Banker, Charnes and Cooper
BOD	Biological Oxygen Demand
CCPI	Clean Coal Power Initiative
CCR	Charnes, Cooper and Rhodes
CCS	Carbon Capture and Storage
CO	Carbon Monoxide
CO <sub>2</sub>	Carbon Dioxide
CRS	Constant Return to Scale
DDF	Directional Distance Function
DEA	Data Envelopment Analysis
DFA	Distribution-Free Approach
DMU	Decision Making Unit
DOE	Department of Environment
DSDF	Directional Slack-based Distance Function
E & E	Electrical and Electronics
EMS	Environmental Management System
EPA	Environmental Protection Agency
EPA	Environmental Protection Agency
ESI	Environmental Sustainability Index
FDH	Free Disposal Hull
FIZ	Free Industrial Zone
FTZ	Free Trade Zone
GAMS	General Algebraic Modeling System
GDP	Gross Domestic Product
GP	Green Productivity
GSCM	Green Supply Chain Management
HE	Hyperbolic Efficiency
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
ML	Malmquist Luenberger
MLEFFC	Malmquist Luenberger Eco-efficiency Change
MLPI	Malmquist Luenberger Productivity Index
MLTC	Malmquist Luenberger Technical Change
NBP	NO <sub>x</sub> Budget trading Programme
N-FIZ	Non-Free Industrial Zone
NO <sub>x</sub>	Nitrogen Oxides
PCB	Printed Circuit Board
PDCA	Plan-do-check-act
PPS	Production Possibility Set
RAM	Range Adjusted Measure
RDM	Range Direction Model
SBM	Slack Based Measure

SDEE	Super DSDF Eco-efficiency
SFA	Stochastic Frontier Approach
SO <sub>2</sub>	Sulphur Dioxide
SPF	Stochastic Production Frontier
TFA	Thick Frontier Approach
TFP	Total Factor Productivity
TSS	Total Suspended Solid
VRS	Variable Return to Scale
WEF	World Economic Forum
WHO	World Health Organization