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Optimization of Life Cycle Assessment-Based Eco-efficiency

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Abstract—**Eco-efficiency (EE) is a concept for quantifying the relationship between economic value creation and environmental impacts. In other words, to be eco-efficient is to add value to goods or services while reducing adverse environmental impacts. In this study, the Eco-indicator 99 was used as a life cycle impact assessment (LCIA) tool to assess environmental impacts. The optimization of EE refers to the maximization of environmental improvement, the minimization of the cost of environmental improvement, or both. Linear programming (LP) was used as an environmental improvement strategy tool to facilitate the optimization of EE. Finally, the optimal strategy for reducing environmental impact in an environmental impact assessment (EIA) was used as a case study.**

***Index Terms*—Eco-efficiency (EF), environmental impact assessment (EIA), life cycle impact assessment (LCIA), linear programing (LP).**

I. Introduction

The World Business Council for Sustainable Development (WBCSD) has defined eco-efficiency (EE) as follows: "Eco-efficiency is achieved by the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life-cycle to a level at least in line with the Earth's estimated carrying capacity." In short, EE is concerned with creating more value with less impact and can be formulated as a ratio

$$\text{Eco-efficiency} = \frac{A}{B}$$

where

A = product or service value

B = environmental impact

or

A = produce price-production cost-pollution control cost

B = environmental impact

or

A = produce price-production cost-pollution controlcost-cost of environmental improvement

B = environmental impact- environmental improvement

The optimization of eco-efficiency is defined as

$$\text{Optimization of eco-efficiency} = \frac{Max.A}{Min.B}$$

where

$Max.A$ = produce price-production cost-pollution controlcost-the minimal cost of environmental improvement

$Min.B$ = environmental impact-the maximally environmental improvement

The denominator, environmental impact, can be evaluated through life cycle impact assessment (LCIA). This study applied the optimization of EE to environmental impact assessment (EIA), as shown in Fig. 1. In an EIA, an EIA committee makes recommendations for environmental improvement and a developer subsequently proposes management plans for achieving the target of environmental improvement. However, the optimal strategy for environmental improvement (pollution reduction) remains unknown. In other words, the key concern for the developer is how to maximize the environmental improvement and minimize the cost of environmental improvement simultaneously.

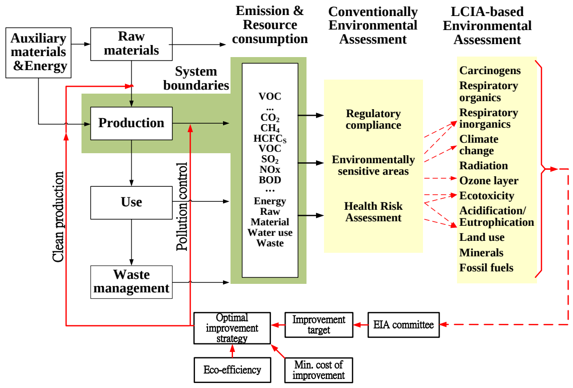

Fig. 1. Framework of the optimization of life cycle assessment-based eco-efficiency in EIA, adapted from [1].

II. Methods and Materials

A. *Evaluating Environmental Impact Using Life Cycle Impact Assessment*

Several studies have reported the feasibility of using LCIA for EIA [1]-[3]. The LCIA phase of an LCA involves the evaluation of potential human health and environmental impacts of the environmental resources and releases identified during the life cycle inventory (LCI). Impact assessment should address ecological and human health effects as well as resource depletion. AnLCIAis used to establish a link between a product or process and its potential

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environmental impacts. A classical LCIA involves selecting the following mandatory elements: impact categories, category indicators and characterization models. At the classification stage, the inventory parameters are categorized and assigned to specific impact categories. In the impact measurement stage, the categorized LCI flows are characterized into common equivalence units, using one of numerous possible LCIA methodologies. These are subsequently summed to provide a total overall impact. The last phase involves "interpretation," which is a systematic technique that identifies, quantifies, checks and evaluates information from the results of the LCI and the LCIA. The results of the inventory analysis and the impact assessment are summarized during the interpretation phase.Eco-indicator 99, which is one of the most widely used impact assessment methods for an LCA was used for this study [4]. Eco-indicator 99 is the successor of Eco-indicator 95, the first endpoint impact assessment method, which allows the environmental load of a product to be expressed in a single score.

B. Optimizing Eco-efficiency by Using Linear Programming

Linear programming (LP) is a method for achieving the most favorable outcome in a mathematical model whose requirements are represented by linear relationships. LP is aparticular type of mathematical programming (mathematical optimization); it is a technique for the optimization of a linear objective function, subject to linear equality and linear inequality constraints. Its feasible region is a convex polytope, which is a set defined as the intersection of a finite number of half spaces, each of which is defined by a linear inequality. Its objective function is a real-valued affine function defined on this polyhedron. An LP algorithm identifies a point in the polyhedron where this function has the lowest (or highest) value, if such a point exists.

Linear programs are problems that can be expressed in canonical form:

Objective function:

Maximize (or Minimize) $z=c_1x_1+c_2x_2+\ldots+c_nx_n$

Functional or definitional constraints:

Subject to :

$a_{11}x_1+a_{12}x_2\leq(=,\geqslant)b_1$

$a_{21}x_1+a_{22}x_2\leq(=,\geqslant)b_2$

.   .

$a_{m1}x_1+a_{m2}x_{2+\ldots}a_{mn}x_n\leq(=,\geqslant)b_3$

Non-negativity constraint:

$x_1\geq 0; x_2\geq 0$

C. Case Study

The case study was conducted using a naphtha cracking plant that is located in Yunlin County, Taiwan (Fig. 2). It is in an offshore industrial zone with a total area of 2,603 ha. Currently, as an alternative before expansion (BE), 61 factories have an annual output of 6,221 t. In response to market demand, the company proposed an expansion plan (alternative after expansion; AE) that would increase the number of factories to 77 and increase production to 8,174 t per year, which is an increase of 31.4% [5].

However, the expansion plan would also increase its emissions of TSP from 3,340 to 4,323 tons per year, SO_2 from 16,000 to 19,788 tons per year, NO_2 from 19,622 to 23,881 tons per year, VOC from 4,302 to 5,389 tons per year and waste-water from 188,000 to 304,500 tons per day. Its inventory flows, including inputs of water, energy and raw materials, as well as releases to air, land, and water, are detailed in Table I.

TABLE I: INVENTORY DATA FOR CASE STUDY

No. of Variable	Name	Chemical formula	Emission (Kg)
X1	Acetaldehyde	C_2H_4O	79.53
X2	Acrolein	C_3H_4O	74.65
X3	Acrylonitrile	C_3H_3N	841.81
X4	Benzene	C_6H_6	504.62
X5	Benzene,1,4-dichloro	$C_6H_4Cl_2$	139.76
X6	Benzene,chloro-	C_6H_5Cl	128.36
X7	Benzene,ethyl-	C_8H_{10}	60.69
X8	Butadiene	C_4H_6	1723.15
X9	Carbon dioxide	CO_2	78,100,000,000
X10	Carbon disulfide	CS_2	14.49
X11	Chloroform	$CHCl_3$	1.70
X12	Dimethyl formamide	C_3H_7NO	1.95
X13	Ethane, 1,2-dichloro-	$C_2H_4Cl_2$	113.02
X14	Ethane,chloro-	C_2Cl_6	60.93
X15	Ethene,chloro-	CH_2CHCl	355.79
X16	Ethene,trichloro-	C_2HCl_3	12.49
X17	Ethyl acrylate	$C_5H_8O_2$	47.67
X18	Ethylene oxide	C_2H_4O	334.86
X19	Formaldehyde	CH_2O	509.27
X20	Hexane	C_6H_{14}	925.53
X21	Methane,monochloro-, R-40	CH_3Cl	225.80
X22	Methane, tetrachloro-, CFC-10	CCl_4	14.63
X23	Methanol	CH_3OH	892.97
X24	Methyl ethyl ketone	C_4H_8O	137.20
X25	Methyl methacrylate	$C_5H_8O_2$	390.67
X26	Naphthalene	$C_{10}H_8$	24.42
X27	Nitrogen oxides	NO_X	23,880,000
X28	Particulates,	PM_{10}	2,160,000
X29	Propylene oxide	C_3H_6O	553.46
X30	Styrene	C_8H_8	1585.95
X31	Sulfur oxides	SO_X	19,790,000
X32	t-Butyl methyl ether	$C_5H_{12}O$	66.97
X33	Toluene	C_7H_8	166.50
X34	TSP	PM_{10}	4,320,000
X35	Vinyl acetate	$C_4H_6O_2$	106.51
X36	VOC,volatile organic compounds	VOCs	5,390,000
X37	Xylene	C_8H_{10}	1,220.86
X38	Ammonia, as N	NH_3，NH_4+	165,600
X39	Chlorine	Cl	10000
X40	Chromium	Cr	13340
X41	COD,Chemical Oxygen Demand	COD	3,630,000
X42	Cyanide	CN^-	1,000
X43	Cadmium	Cd	1,560
X44	Manganese	Mn	5,560
X45	Mercury	Hg	110
X46	Phosphate	H_3PO_4	11,110
X47	Phosphorus, total	P	24,450
X48	Selenium	Se	16,670
X49	Zinc	Zn	17,780
X50	Arsenic	As	17,780
X51	Lead	Pb	21,120

III. Results

A. Life Cycle Impact Assessment for Environmental Impact Assessment: Case Study

The results of using the Eco-indicator 99 for assessing the outcome of the case study are shown in Table II, indicating that the most negative impact on human health is climate change and the most negative impact on the quality of the ecosystem is acidification/ eutrophication.

TABLE II: Eco-indicator 99 Results for Case Study Using [2]

Impact Category (midpoint)	Unit	BE	AE
Carcinogens	DALY	1.030E-01	1.309E-01
Respiratory organics	DALY	2.785E+00	3.491E+00
Respiratory inorganics	DALY	3.255E+03	4.018E+03
Climate change	DALY	1.419E+04	1.641E+04
Radiation	DALY	--	--
Ozone layer	DALY	1.825E-02	2.320E-02
Ecotoxicity	PDF*m^2*yr	6.756E+06	1.094E+07
Acidification/ Eutrophication	PDF*m^2*yr	1.287E+08	1.570E+08
Human Health	DALY	1.745E+04	2.043E+04
Ecosystem Quality	PDF*m^2yr	1.355E+08	1.679E+08

BE: before the expansion; AE:after the expansion.

B. Scenarios of Possible Improvement

According to the result of LCIA, not only the amount of pollution emission also the damage to human health and ecosystem quality are provided so that the EIA committee is easier to judge the significance of environmental impact. Subsequently, the committee may ask the developer to commit to improve the environmental impact by reducing emission. The study assumes nine scenarios of possible improvement as follows, that are detailed in Table III.

- Scenario 1: 10% reduction of the impact on human health
- Scenario 2: 20% reduction of the impact on human health
- Scenario 3: 50% reduction of the impact on human health
- Scenario 4: 10% reduction of the impact on the quality of the ecosystem
- Scenario 5: 20% reduction of the impact on the quality of the ecosystem
- Scenario 6: 50% reduction of the impact on the quality of the ecosystem
- Scenario 7: 10% reduction of the impact on human health and the quality of the ecosystem
- Scenario 8: 20% reduction of the impact on human health and the quality of the ecosystem
- Scenario 9: 50% reduction of the impact on human health and the quality of the ecosystem

C. Cost of Environmental Improvement

Cost of environmental improvement can be formulated as follows:

Cost of environmental improvement
＝cost of pollution reduction
－benefit of pollution reduction

The cost of pollution reduction includes capital, equipment, material, and human resources for the operation and maintenance of pollution control and reduction; the benefit of pollution reduction refers to the savings of emissions tax because of the pollution reduction. The unit costs of environmental improvement for all variables are summarized in Table IV.

TABLE III: Nine Scenarios of Environmental Improvement

Endpoint	Impact for AE	Scenario		
		No.	Target of reduction	Allowance of emission
Human health	20,433 (DALY)	1	2,043	18,389
		2	4,086	16,346
		3	10,216	10,216
Ecosystem quality	266,448,452 (PDF*m^2*yr)	4	26,644,845	239,803,607
		5	53289690	213,158,762
		6	133,224,226	133,224,226
(A) Human health (B) Ecosystem quality	(A)20,433 (B)266,448,452	7	(A)2,043 (B)26,644,845	(A)18,389 (B)239,803,607
		8	(A)4,086 (B)53,289,690	(A)16,346 (B)213,158,762
		9	(A)10,216 (B)133,224,226	(A)10,216 (B)133,224,226

D. Optimizing Eco-efficiency

The optimization of EE is performed using LP, which comprises the following four parts.

- Objective function: Minimize cost of environmental cost.
- Constraint 1: Environmental improvement of impact on human health is greater than or equal to the target reduction.
- Constraint 2: Environmental improvement of impact on the quality of the ecosystem is greater than or equal to the target reduction.
- Constraint 3: Emissions reduction of each variable is less than or equal to its emissions but not negative.

TABLE IV: Unit Cost of Environmental Improvement

No of variable	Unit cost of pollution reduction (NTD/Kg)
X1-X8	30.6
X9	615.72
X10-X26	30.6
X27	51.30
X28-X30	30.6
X31	73.22
X32-X33	30.6
X34	25.55
X35	30.6
X36	5.6
X37	30.6
X38	31,600
X39	3,948
X40	31600
X41	79,000
X42	6,320
X43	158,000
X44	249.76
X45	158,000
X46	15,800
X47	63,200
X48	12,640
X49	6,320
X50	3,160
X51	6,320

Scenarios 1, 2 and 3 are the environmental improvement of impact on human health with targets of 10%, 20% and 50% reduction, respectively; their optimal reductions are shown in Table V - Table VIII, respectively. Avariable does not reduce its emission if it is not listed in these tables.

TABLE V: ENVIRONMENTAL IMPROVEMENT FOR SCENARIO 1

No.	Emission (Kg)	Reduction (Kg)	Reduction (%)
X18	334.86	334.86	100
X22	14.63	14.63	100
X27	23,880,000	13840,900	57.96
X28	2,160,000	2,160,000	100

TABLE VI: ENVIRONMENTAL IMPROVEMENT FOR SCENARIO 2 (X1-X23)

No.	Emission (Kg)	Reduction (Kg)	Reduction (%)
X1	79.53	79.53	100
X2	74.65	74.65	100
X3	841.81	841.81	100
X4	504.62	504.62	100
X7	60.69	60.69	100
X8	1723.15	1723.15	100
X9	78,148,750,000	308,291,300	0.39
X11	1.7	1.70	100
X13	113.02	113.02	100
X15	355.79	355.79	100
X16	12.49	12.49	100
X18	334.86	334.86	100
X19	509.27	509.27	100
X20	925.53	925.53	100
X21	225.8	225.80	100
X22	14.63	14.63	100
X23	892.97	892.97	100

TABLE VII: ENVIRONMENTAL IMPROVEMENT FOR SCENARIO 2 (X24-37))

No.	Emission (Kg)	Reduction (Kg)	Reduction (%)
X24	137.2	137.20	100
X27	23,880,000	23,880,000	100
X28	2,160,000	2,160,000	100
X29	553.46	553.46	100
X30	1,585.95	1585.95	100
X31	19,790,000	19,790,000	100
X32	66.97	66.97	100
X33	166.5	166.50	100
X36	5,390,000	5,390,000	100
X37	1,220.86	1,220.86	100

TABLE VIII: ENVIRONMENTAL IMPROVEMENT FOR SCENARIO 3

No.	Emission (Kg)	Reduction (Kg)	Reduction (%)
X1	79.53	79.53	100
X2	74.65	74.65	100
X3	841.81	841.81	100
X4	504.62	504.62	100
X7	60.69	60.69	100
X8	1,723.15	1723.15	100
X9	78,148,750,000	29,498,460,000	37.75
X11	1.70	1.70	100
X13	113.02	113.02	100
X15	355.79	355.79	100
X16	12.49	12.49	100
X18	334.86	334.86	100
X19	509.27	509.27	100
X20	925.53	925.53	100
X21	225.80	225.80	100
X22	14.63	14.63	100
X23	892.97	892.97	100
X24	137.2	137.2	100
X27	23,880,000	23,880,000	100
X28	2,160,000	2,160,000	100
X29	553.46	553.46	100
X30	1585.95	1585.95	100
X31	19,790,000	19,790,000	100
X32	66.97	66.97	100
X33	166.5	166.5	100
X36	5,390,000	5,390,000	100
X37	1,220.86	1,220.86	100

IV. DISCUSSION

TABLE IX: IMPROVEMENT EFFICIENCYOF VARIABLES

No.	Characterization factor (DALY/Kg)	Unit cost of pollution reduction (NTD/Kg)	Improvement efficiency (DALY/NTD)	Rank
X1	1.58E-06	30.607	5.15E-08	16
X2	1.70E-06	30.607	5.55E-08	15
X3	1.69E-05	30.607	5.52E-07	10
X4	2.97E-06	30.607	9.70E-08	12
X5	0	30.607	0	28
X6	0	30.607	0	28
X7	1.53E-06	30.607	5.00E-08	17
X8	1.77E-05	30.607	5.77E-07	9
X9	2.10E-07	615.715	3.41E-10	27
X10	0	30.607	0	28
X11	2.72E-05	30.607	8.88E-07	7
X12	0	30.607	0	28
X13	3.02E-05	30.607	9.85E-07	6
X14	0	30.607	0	28
X15	2.09E-07	30.607	6.83E-09	25
X16	7.78E-07	30.607	2.54E-08	21
X17	0	30.607	0	28
X18	1.83E-04	30.607	5.98E-06	3
X19	2.10E-06	30.607	6.86E-08	14
X20	1.02E-06	30.607	3.33E-08	19
X21	3.94E-05	30.607	1.29E-06	5
X22	1.84E-03	30.607	6.01E-05	1
X23	2.81E-07	30.607	9.18E-09	24
X24	8.09E-07	30.607	2.64E-08	20
X25	0	30.607	0	28
X26	0	30.607	0	28
X27	8.91E-05	51.3064	1.74E-06	4
X28	3.75E-04	30.607	1.23E-05	2
X29	1.17E-05	30.607	3.82E-07	11
X30	2.44E-08	30.607	7.97E-10	26
X31	5.46E-05	73.2261	7.46E-07	8
X32	3.32E-07	30.607	1.08E-08	23
X33	1.36E-06	30.607	4.44E-08	18
X34	0	25.5595	0	28
X35	0	30.607	0	28
X36	6.46E-07	30.607	2.11E-08	22
X37	2.21E-06	30.607	7.22E-08	13
X38	0	3948	0	28
X39	0	79000	0	28
X40	0	6320	0	28
X41	0	249.76	0	28
X42	0	31600	0	28
X43	0	31600	0	28

X44	0	15800	0	28
X45	0	158000	0	28
X46	0	63200	0	28
X47	0	12640	0	28
X48	0	158000	0	28
X49	0	6320	0	28
X50	0	6320	0	28
X51	0	3160	0	28

The optimal strategies of reducing emission are summarized in the following guidelines.

- The selected variables are all basic solutions.The variables X18, X22, X27 and X28 in Scenario 1 are basic solutions because their reduced costs are zero, as shown in Table V.
- The variables are reduced by the ranks of theirimprovement efficiencies.The improvement efficiency of a variable is defined as follows:

Improvement efficiency of a variable(DALY/NTD or PDF*m^2*yr/NTD)

$$= \frac{\text{Charactorization factor}\,(DALY / Kg \; or \; PDF * m \wedge 2 * yr / Kg}{\text{Unit cost of pollution reduction}\,(NTD / Kg)}$$

For example, the characterization factor of variable X1 (acetaldehyde) is 1.58E-06 (DALY/Kg) and its unit cost of pollution reduction is 30.607 (Kg/NTD); therefore, its improvement efficiency is 5.15E-08 (DALY/NTD). Thus, the improvement efficiencies of all variables are derived, as shown in Table IX.

V. Conclusion

In this study, the optimization of LCIA-based EE was most favorably applied in EIA. The EIA committee recommends environmental improvements and asks developers to commit by providing targets for pollution reductions. For developers, the optimal strategy is to achieve the targets at minimal costs, which refer to EE. The findings of this study reveal that targets are approached by the ranks of improvement efficiency of variables. Future studies should further investigate the improvement efficiency when simultaneously considering human health and the quality of the ecosystem. Placing improvement on impact categories (midpoints) rather than on endpoints requires more effort. Finally, how to develop a trade-off strategy of environmental improvement is a crucial consideration when targets are multiple and conflict.

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