Performance Evaluation of Green Supply Chains: A DEA-based Approach for the Chemical Industry

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***Abstract*—Traditionally, researchers and practitioners measure the performance of green supply chains from the aspects of economy and environment. Nowadays, human capital is given much attention in Corporate Social Resposibility (CSR) but is often not included in the performance measures. This research covers the an application of data envelopment analysis (DEA) slacks-based model to a multinational chemical manufacturer to minimize both input and bad output variables of both the environmental aspect, covering energy consumption, water intake, carbon dioxide(CO_2), voltile organic compound(VOC), solid waste, and the social aspect covering employees' working hours and total recordable (injury and illness) rate. The model also maximizes the good output, finished good products, to satisfy customers and other stakeholders. This technique results in a more holistic result and decision making model for benchmarking the performance of multiple manufacturing sites in a multinational company in Asia.**

***Index Terms*—Green Supply Chains, Data Envelopment Analysis (DEA), Slacks-based Model**

I. Introduction

Enterprises are obliged to comply with regulatory requirements aimed at addressing the issues of environmental deterioration and global warming require to meet their customers' expectations, e.g. the European Union (EU) has imposed restrictions on the use of certain hazardous substances in electrical and electronic equipment (ROHS) to be sold in the EU, prohibiting the sale of items containing these hazardous materials [1]. The EU also implemented the REACH (Registration, Evaluation, Authorization Restriction of Chemical Substance) regulations to protect human health and the environment [2]. These regulations require chemical companies to operate their supply chains with minimum impact on the environment and no harm to people's health and safety.

Srivastava (2007) defined green supply chains as integrating environmental techniques into their operation, covering the processes of supplier selection, manufacturing, transportation, distribution, and product end of life [3]. Sarkis (2003) identified the critical elements in the green supply chain decision framework, covering product life cycle, operational life cycle and organizational performance measurements related to waste generation, environmental practices. He also identified alternatives for improving the performance of supply chains [4]. The satisfaction of stakeholders is so one of the main factors driving enterprises towards sustainable and green supply chains.

Examination of the processes within supply chains shows that both desirable and undesirable outputs can be generated simultaneously; therefore, it is difficult, if not impossible, to produce only desirable outputs without also generating undesirable outputs [5]. In the operation of their supply chains, businesses seek a decision model for sustainable improvement, minimizing the inevitable undesirable outputs from the processes. DEA models have been widely applied to assessing and reducing the undesirable outputs to improve the performance of green supply chains. The undesirable outputs impact upon on the returns to scale and require further investigation via DEA, e.g. Zhou et al. (2008) measured environmental efficiency including carbon emissions for eight regions in the world with DEA variant returns to scale and non-increasing returns to scale in a mixed measure. In addition most research is based on constant returns to scale in a pure measure [6].

This article is an application case of performance evaluation of green supply chains using a DEA model to analyze the manufacturing process in a multinational chemical company in Asian countries. It begins with an introduction to green supply chains. Subsequently, we propose a methodology to analyze the data from an application case. From the data analysis and results, we develop discussions and conclusions.

II. Methodology

DEA (Data Envelopment Analysis) is a mathematical programming based approach for measuring the productive efficiency of decision making units (DMUs) with weighted multiple outputs against weighted multiple inputs. It is based on the idea of production frontier in micro-economics. The CCR model and the BCC model are two basic radial DEA models, in which the input

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excess and output shortfall are called slacks, and the projection θ*=1 represents optimal performance without slacks. This is called "CCR-efficient" [7].

Dyson et al. (2001) found that the undesirable outputs e.g. the emission of atmospheric pollutants are factors with a negative effect on DEA applications. From part of the requirements, it can remove undesirable outputs by changing them into inputs; thus minimizing both the inputs and undesirable outputs [8]. Therefore, we applied the slacks-based model, SBM, to analyze the performance of green supply chains as it contains undesirable outputs as well as the compound variables for energy-environment-social factors for efficiency measurement at higher discrimination power.

According to Tone (2001), the definition and computational scheme of the SBM model is as follows: To define matrices of n inputs (X) and outputs(Y) by DMUs [9].

$$P = \{(x, y) | x \geq X\lambda, y \leq Y\lambda, \lambda \geq 0\} \tag{1}$$

,where λ is the non-negative vector of R^n. We could apply λ in the BCC model and the constraint is $\sum_{j=1} \lambda_j = 1$, the mathematics of DMU (x_0, y_0) is then as follows:

$$x_0 = X\lambda + s^- \tag{2}$$

$$y_0 = Y\lambda - s^+ \tag{3}$$

,where λ≥0,s^-≥0 and s^+≥0. Vectors $s^- \in R^m$ and $s^+ \in R^s$ represent input excess and output shortfall respectively. Under the conditions of X>0 and λ≥0, this results in

$$x_0 \geq s^- \tag{4}$$

We could define an equation ρ by using S^- and S^+ as follows.

$$\rho = \frac{1 - \frac{1}{m}\sum_{i=1}^{m} s_i^- / x_{i0}}{1 + \frac{1}{s}\sum_{r=1}^{s} s_r^+ / y_{r0}} \tag{5}$$

ρ satisfies two properties simultaneously regarding the measure: (1) unit invariant: the units of the data would be make no difference; (2) monotone: with every slack in input and output excess increasing or decreasing together the same direction. In the green supply chain application, it can identify the effectiveness of resource utilization according to the two properties of slacks-based measure in order to evaluate the performance. The most effective possible DMU performance is represented by the efficiency frontier value of 1; in contrast, those DMUs with values below 1 are not at the frontier. Therefore, (4) can be represented as:

$$0 < \rho \leq 1 \tag{6}$$

An equation (5) can be represented as follows:

$$\rho = \left(\frac{1}{m}\sum_{i=1}^{m} \frac{x_{i0} - s_i^-}{x_{i0}}\right)\left(\frac{1}{s}\sum_{r=1}^{s} \frac{y_{r0} + s_r^+}{y_{r0}}\right)^{-1} \tag{7}$$

The first part of the above equation is $x_{i0} - s_i^- / x_{i0}$ in which i is the rate of reduction of input excess; the second part of the above equation is $(y_{r0} + s_r^+)/y_{r0}$ in which r is the rate of increase of output shortfall.

To determine the efficiency of (x_0, y_0), the mathematics can be defined as follows:[SBM]

$$\text{minimize} \quad \rho = \frac{1 - \frac{1}{m}\sum_{i=1}^{m} s_i^- / x_{i0}}{1 + \frac{1}{s}\sum_{r=1}^{s} s_r^+ / y_{r0}} \tag{8}$$

$$\text{subject to} \quad x_0 = X\lambda + s^- \tag{9}$$

$$y_0 = Y\lambda - s^+ \tag{10}$$

$$\lambda, s^-, s^+ \geq 0 \tag{11}$$

The model is applied to a leading global manufacturer of chemicals which operates in over 80 countries in North Americas, Europe, Asia and Latin America. Its long-term financial business goals cover revenue, profit and working capital, and the non-financial goals cover safety, environment, efficiency, and diversity. The company has three business units with its revenue structure- Decorative Paints makes 33.93% of global sales, Performance Coatings makes 32.69%, and Specialty Chemicals makes 33.76%. The proposed green supply chains method was first applied to the Decorative Paints plants in Asia.

The company used as the application case pays much attention to health, safety, and environment in supply chain operations. There are sustainability related targets in its long term strategic development plan and the company's inclusion in the Dow Jones Sustainability Index demonstrates its ambitions in corporate social responsibility. Clearly it is believed that caring for people and the environment is essential to further business growth and drive profit.

Table I is the green supply chain indices for the multinational chemical company studied covering 13 of its production plants in Asia, represented by Decision Making Units (DMUs) AQ1 to DMU MQ8 for 8 quarters from 2009 to 2010. A total of 13*8=104 DMUs were analyzed for green manufacturing efficiency to identify benchmarks and opportunities for improvement. Figure 1 shows the inputs, desirable and undesirable outputs for the application case. These green manufacturing performance indicators are monitored in every plant, at regional business unit level, at corporate level and used as supporting data for further analysis.

TABLE I.
THE DMUS WITH RESPECTIVE LOCATION AND COUNTRIES

Location (Abbreviation)	DMUs	Country	SBU
Shanghai, SH	AQ1-AQ8	China	North Asia
Guangzhou, GZ	BQ1-BQ8	China	North Asia
Lang Fang, LF	CQ1-CQ8	China	North Asia
Chung Li, CL	DQ1-DQ8	Taiwan	North Asia
Hyderabad, HB	EQ1-EQ8	India	South Asia
Mohai, MH	FQ1-FQ8	India	South Asia
Thane, TH	GQ1-GQ8	India	South Asia
Cikarang, CK	HQ1-HQ8	Indonesia	South East Asia
Ho Chi Ming City, HCMC	IQ1-IQ8	Vietnam	South East Asia
Jurong, JR	JQ1-JQ8	Singapore	South East Asia
Nilai, NL	KQ1-QK8	Malaysia	South East Asia
Laksi, LK	LQ1-LQ8	Thailand	South East Asia
Binh Duong, BD	MQ1-MQ8	Vietnam	South East Asia

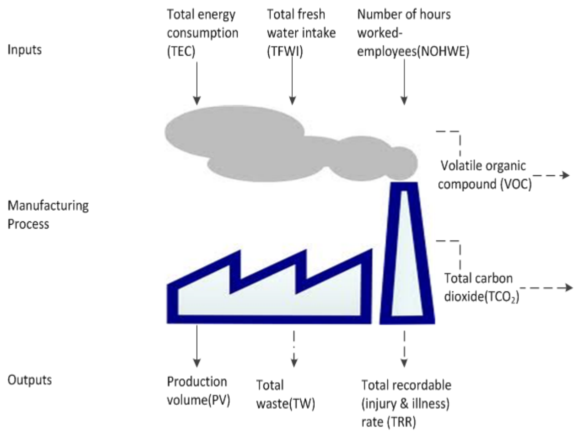

Figure 1. The indices of green supply chains of chemical company-inputs, good output and bad (undesirable) outputs

III. Results

Table II shows the statistical analysis of inputs/outputs in the form of maximum, minimum, and average values and standard deviation. Table III is the input and output correlation matrix. The abbreviation of variables for all inputs, good outputs and bad outputs is described at table 2. There is a high correlation between TFWI and PV represented by a value of 0.88; the next most significant correlation is between TEC and PV at 0.80; then TCO_2 and PV at 0.79; TW and PV at 0.78; NOHWE and PV at 0.76; VOC and PV at 0.03 and TRR and PV at -0.03. The correlations between VOC and PV and TRR and PV are much lower, even negative for the latter. The correlation between VOC and PV is very low at 0.03 due to the fact that the production volume is dominated by water based products which generate no VOCs. The negative correlation between TRR and PV at -0.03 is also quite low because the company has the stringent Health, Safety, Environment (HSE) systems and has succeeded in reducing the number of injuries and illnesses to very low numbers.

Table IV shows the difference between constant returns to scale (CRS) and variable returns to scale (VRS).

These therefore do not increase in direct relation to production even though increased production requires a greater number of hours to be worked mean value of 0.66; the VRS minimum value is 0.34, 15% higher than for CRS minimum value of 0.30; the VRS number of efficient DMUs is 26, 18% higher than the CRS number of efficient DMUs of 22. It can be seen the values at VRS are much higher than those obtained by using CRS in DEA. This is because the output slacks are not included in the efficiency measure. Therefore, we applied the input-oriented slacks-based measure of efficiency at the assumption of constant returns to scale (SBM CRS) model to increase the consistency of the performance evaluation of green supply chains in Asian plants [10]. We used the software DEA SOLVER for the SBM Input Oriented Model and STATISTICA to validate the significance calculations and levels.

Table V shows the statistical analysis of green supply chain performance in the Asian plants using quarterly data from 2009 and 2010 and figure 2 is the line plot of the green supply chain performance. The ranking of the performance of green supply chains by location is as follows. As of 2010Q1, the Corporate Sustainability Department/Team launched a key performance index of operational eco efficiency (OEE) to cascade to every plant including Asia in an attempt to improve green supply chain management performance over the 5 year period to 2015. Operational eco efficiency covered energy, waste and water conservation improvement actions proposed and implemented by every plant annually. The Corporate Sustainability Department/Team monitored the green supply chain performance via the operational eco efficiency index for driving continuous improvement and thus contributing to the welfare of our planet.

TABLE II.
Statistics For Inputs/Outputs

	Good output	Input			Bad(Undesirable outputs)			
	PV	TEC	TFWI	NOHWE	VOC	TW	TCO_2	TRR
Max	30,616..56	12..33	14.64	550,255.00	101.80	497.26	1,072.09	3.00
Min	966.51	0.87	0.77	28,224.00	-	18.74	43.28	-
Average	9,262.59	5.16	6.21	92,749.52	6.86	149.24	418.12	0.15
SD	6,678.63	2.97	3.47	106,949.03	11.92	123.63	266.06	0.46

TABLE III.
Input And Output Correlation Matrix

	Good output	Input			Bad(Undesirable outputs)			
	PV	TEC	TFWI	NOHWE	VOC	TW	TCO_2	TRR
PV	1.00	0.80	0.88	0.76	0.03	0.78	0.79	-0.03
TEC	0.80	1.00	0.79	0.65	0.20	0.68	0.95	0.00
TFWI	0.88	0.79	1.00	0.55	0.10	0.71	0.75	0.03
NOHWE	0.76	0.65	0.55	1.00	0.07	0.57	0.61	0.12
VOC	0.03	0.20	0.10	0.07	1.00	0.08	0.25	0.02
TW	0.78	0.68	0.71	0.57	0.08	1.00	0.56	0.14
TCO_2	0.79	0.95	0.75	0.61	0.25	0.56	1.00	0.07
TRR	-0.03	0.00	0.03	0.19	0.03	0.14	0.07	1.00

TABLE IV.
DIFFERENCE BETWEEN SBM CRS AND VRS VALUE

	CRS	VRS	Difference
No. of DMUs	104	104	0%
Average	0.66	0.78	19%
SD	0.22	0.21	6%
Maximum	1	1	0%
Minimum	0.30	0.34	15%
No. of efficient DMU	22	26	18%
No. of inefficient DMU	82	78	5%

TABLE V.
QUARTERLY STATISTICAL ANALYSIS OF GREEN SUPPLY CHAINS' PERFORMANCE IN ASIAN PLANTS-2009~2010

Variable	Valid N	Mean	Minimum	Maximum	Std. Dev.
CK	8	0.9369	0.7260	1.0000	0.1175
TH	8	0.8963	0.6918	1.0000	0.1243
HCMC	8	0.8513	0.6181	1.0000	0.1438
BD	8	0.8154	0.7133	1.0000	0.1170
SH	8	0.7660	0.5410	1.0000	0.2097
MB	8	0.7009	0.4439	1.0000	0.2117
GZ	8	0.6296	0.5187	0.7708	0.1008
LF	8	0.6084	0.2976	1.0000	0.2670
JR	8	0.5995	0.5362	0.6668	0.0430
NL	8	0.4940	0.3950	0.5526	0.0483
CL	8	0.4257	0.3471	0.4889	0.0470
LK	8	0.4206	0.3353	0.5119	0.0654
MH	8	0.3809	0.3262	0.4338	0.0355

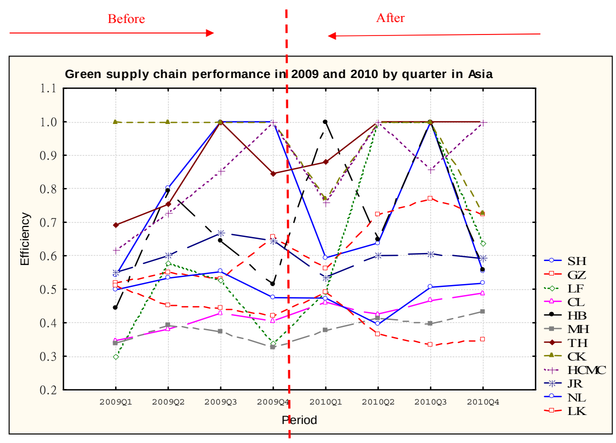

Figure 2. Green supply chain management performance in 2009 and 2010 by quarter in Asia by locations

IV. DISCUSSIONS

This measure was used to cascade operational eco efficiency objectives from corporate level, to region and country levels. The Corporate team can use the measures to monitor whether green supply chain performance can be driven by operational eco efficiency in an efficient manner.

Table VI shows the statistics of the quarterly performance of green supply chains in Asia before and after the implementation of operational eco efficiency projects. The average green supply chain performance in 2009 and 2010 was 0.6159 and 0.6691 respectively. The p value is equal to 0.05 which is less than 0.1, demonstrating that there has been a significant change in performance. In Figure 3 the box and whisker plot shows the significant difference of green supply chain performance in Asian plants before and after operational eco efficiency project implementation. We can thus conclude that operational eco efficiency can be used to drive green supply chain performance in a multinational chemical company, in addition to the implementation of a strong health, safety and environment management system.

TABLE VI.
QUARTERLY PERFORMANCE STATISTICS OF GREEN SUPPLY CHAINS IN ASIA BEFORE AND AFTER IMPLEMENTATION OF OPERATIONAL ECO EFFICIENCY (OEE) PROJECTS

T-test for Dependent Samples (performance of green supply chains in 2009 and 2010 by quarter in Asia.sta)
Marked differences are significant at $p<0.10000$

	Mean	Std. DV.	N	Diff.	Std. DV	t	df	p
Before	0.62	0.22	48	-0.05	0.19	-1.90	47	0.05
After	0.67	0.23						

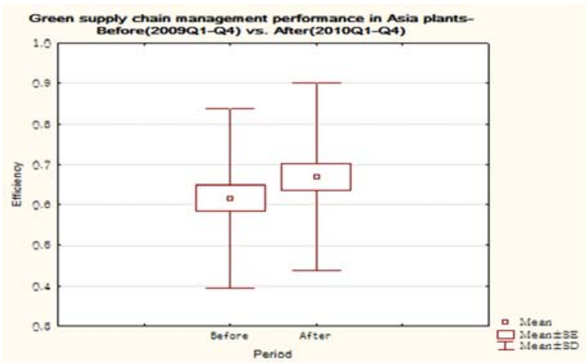

Figure 3. Box and whisker plot of green supply chain management performance in Asia plants before and after implementation of Operational Eco Efficiency (OEE) projects

The limitation of this paper is that the data was only available from the aspects of environment and society for Asian locations. This model could also be used to evaluate the performance of green supply chains in other regions, businesses, industries or multinational companies or added the aspect of economic which has the multiple locations whose performance needs to be monitored and managed over a period of time.

V. CONCLUSIONS

Driving the improvement of green supply chains is crucial from many aspects, such as preventing environmental deterioration, complying with legal regulations and stakeholders' requirements. This is an application case of a multinational chemical company facing green issues of undesirable outputs in manufacturing process to deliver good outputs in order to satisfy consumers and stakeholders. Alongside the more traditional environmental indices- air emissions of carbon dioxide, volatile organic compounds, waste generation, consumption of fresh water and energy, health and safety related indices such as total recordable (injury and illness) rate by input man-hours can be included to make the performance evaluation of green supply chains more holistic.

We propose that the DEA Slacks-Based Model can be used as a decision model to evaluate and benchmark the performance of green supply chains across multiple locations aiming to drive continuous improvement. This will aid them to continuously improve their different operations by transferring learning from the best performing location in all variables. This in turn will help the company run its business in green and sustainable manner and deliver long term competitive advantage in its industry.

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