Sustainability Assessment by Fuzzy Evaluation of Hanwha Chemical

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Student 2

Abstract

Using the SAFE (*Sustainability Assessment by Fuzzy Evaluation*; developed by Phillis et al.) model, I assessed the sustainability of Hanwha Chemical, a petrochemical company based in South Korea. The particular model I designed for Hanwha (Figure 1) uses a total of 20 basic indicators that cover a wide range of environmental, societal, or economic impacts to hierarchically assess the overall sustainability of the company.

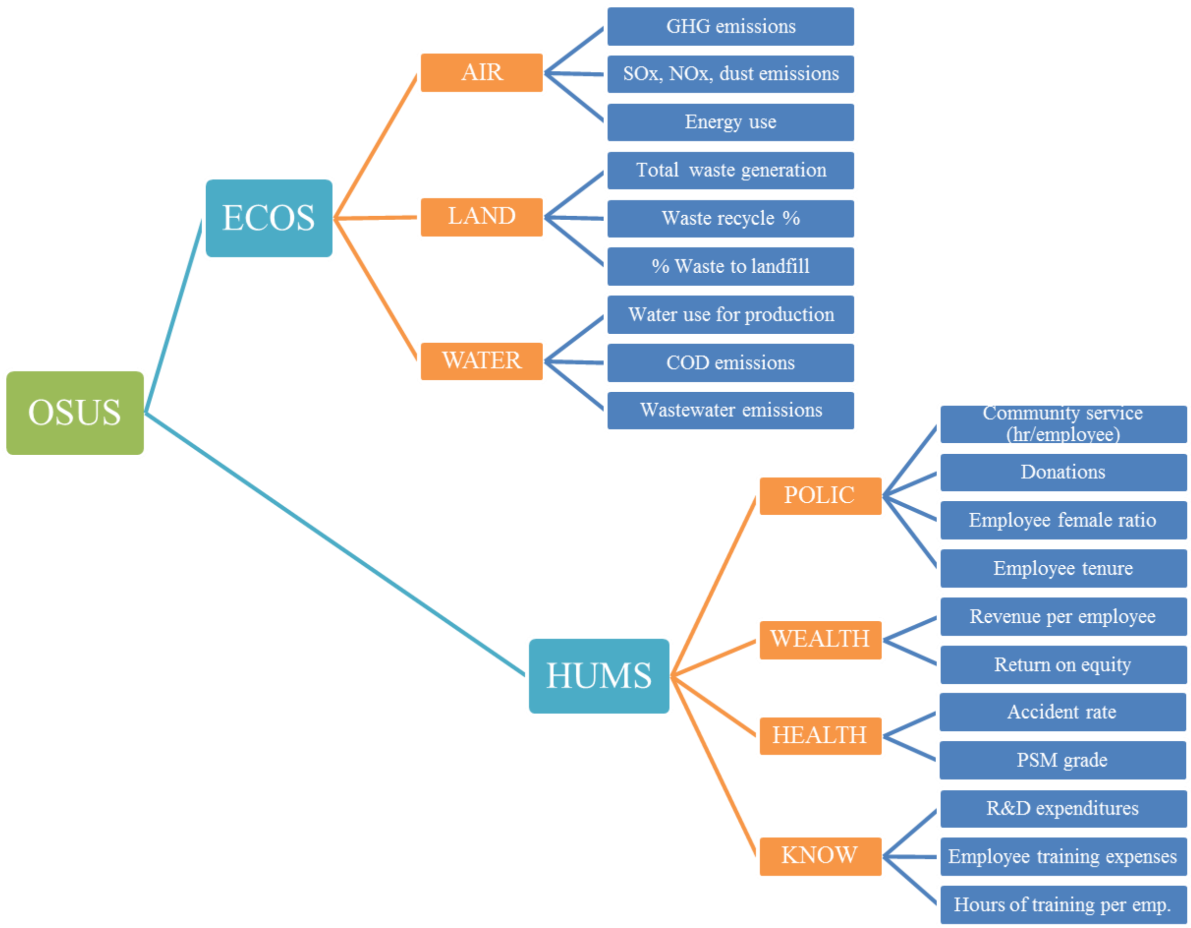

Figure 1 The SAFE model for Hanwha Chemical

The results indicate that Hanwha's operations are most sustainable in its impact on water and employee health, while least sustainable on its impact on land and on its unsatisfactory scale of investment in R&D and employee education. Based on its overall sustainability (OSUS) of 0.55, based on a [0, 1] scale with 1 being fully sustainable, I concluded that Hanwha is a *fairly sustainable* corporation with respect to other comparable companies in the diversified chemicals sector.

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Introduction

Today's market and society demand corporations to be *sustainable* in their operations. A sustainable corporation is one that generates commercial success without causing harm to, if not further improving, the environment and the welfare of society. To evaluate how sustainable a company's operations are, one has to quantitatively assess both the socioeconomic and the environmental impacts of the corporation through collecting and analyzing data on its activities such as emissions, process efficiencies, economic performance, policies, impact of products, programs for employees and community, etc.

Because sustainability is a complex concept that consists of numerous aspects that are often qualitative and subjective, an assessment tool based on fuzzy logic called the *SAFE model* becomes highly effective. The *SAFE model* was initially developed for sustainability assessment of nations by Phillis *et al*. in 2001. It uses indicators of environmental integrity, economic efficiency, and social welfare as inputs and employs hierarchical fuzzy inference to provide a sustainability measure.[i] Because it allows flexibility in the choice of indicators, SAFE can be adopted to evaluate sustainability of corporations. In this study, I selected many of my indicators based on the Global Reporting Initiative (GRI) framework, which is one of the world's most prevalent standards for sustainability reporting of corporations about economic, environmental, social and governance performance. [ii]

The overall sustainability (OSUS) in the *SAFE model* encompasses two broad components or primary indicators, namely, ecological sustainability (ECOS) and human sustainability (HUMS). The ECOS consists of four secondary indicators: water quality (WATER), land integrity (LAND), air quality (AIR), and biodiversity (BIO , which is omitted in the Hanwha model due to lack of data). The HUMS is also comprised of four secondary indicators: political aspects (POLIC), economic welfare (WEALTH), health (HEALTH), and education (KNOW).[i]

Hanwha Chemical is a South Korean petrochemical company that specializes in the production of commodity chemicals like chloro-alkali products (sodium hydroxide and chlorine), polymer resins such as LDPE, LLDPE, and PVC, and renewable energy products like polysilicon, solar panels/modules, and secondary battery materials. Established in 1965, it has steadily grown into a competitive chemical company with an annual production capacity of 4.5 million tons, net sales of 3,600 billion won ($3.2 billion), and 2,200 employees. Hanwha competes against LG Chemical (chloro-alkali), SK Chemical (polymers), domestically, and Formosa Plastics (PE, PVC, chloro-alkali) and Dow Chemical (cross linkable-PE), internationally. Headquartered in Seoul, it has two major plants in Ulsan and Yeosu industrial complex in Korea. Since 2000, Hanwha bi-annually publishes a corporate report, a financial report, and a sustainability report, from which most of the necessary data were readily obtained for this study.

Model Description

(1-1) SELECTION OF BASIC INDICATORS

The following basic indicators were selected to represent various aspects of environmental and socioeconomic impacts of Hanwha Chemical:

AIR

1) *Direct greenhouse gas (GHG) emissions* (metric tons CO_2 equivalent emitted per ton of product) are the main cause of climate change, and thus are governed by the United Nations Framework Convention on Climate Change (UNFCC) and the subsequent Kyoto Protocol.[iii] Lower emissions of GHG imply that the company is more sustainable due to its decreased risk from environmental regulations, reduced impact on the global ecosystem, and also due to different incentive systems (such as trading climate certificates). GHG is listed as one of the GRI indicators (EN17).

   I set the target value to be Hanwha's corporate goal to reduce GHG emissions by 20% from 2010 (T_{GHG}=0.37) and the threshold of undesirable values at the maximum over all investigated companies (Eastman) U_{GHG}=0.9 metric tons CO_2 equivalent per ton of product.

2) *SOx, NOx, and dust emissions* (kg per ton of product) measure the scale of the company's impact on air quality. Air pollutants have adverse effects on the environment and human and animal health. Concerns on deterioration of air quality, acidification, forest degradation, as well as public health led to environmental regulations on various scales to control air emissions. Reductions in regulated pollutants would lead to improved health conditions for workers and communities, enhanced relations with affected communities, and thus to the ability to maintain/expand operations. [iii] It is also one of the GRI indicators (EN20).

   The target value for the combined air emissions is set at 10% of the 2010 value, T_c=0.001 kg per ton of product. Any value above the average over two global corporations that have comparatively large emissions (Dow and BASF), U_c=0.35, is not sustainable.

3) *Energy consumption* (kJ per ton of product) indicates the company's ability to use energy efficiently which has an indirect but strong correlation to its impact on air because most conventional energy sources emit air pollutants as by-products. Hanwha relies heavily on non-renewable energy sources such as natural gas, which makes this indicator an appropriate measure of its impact on air.

   The target value for this indicator is T_c=7.41 kJ per ton product, which is Hanwha's all-time low record (2007) over the last decade. The undesirable threshold is set at U_c=10.2, which is the average of the two largest values among the investigated companies (Dow and Eastman).

LAND

4) *Total solid waste generated* (metric tons per ton of product) is the mass of solid waste that is generated as byproducts of the company's production processes. This indicator demonstrates the level of progress the company has made toward waste reduction efforts and also potential

improvements in process efficiency and productivity. Lower waste generation means lower costs for materials (as less is being wasted), processing and disposal, in addition to reduced pollution of land and greater amount of land available to the ecosystem for other purposes (since a large percentage of total waste is dumped into a landfill). This indicator is a part of GRI guidelines (EN22).

The target value for solid waste generation is set at Hanwha's all-time low value (2009) at T_c=7.13 tons per ton of product; any value above the maximum over all companies (Dow) at U_c=24.6 is considered unsustainable.

5) *Percent waste recycled (% of total)* is a measure of how efficient the company is at reusing its own waste and thus controlling its ecological footprint. The higher the recycling rate, the lower the company's impact on the ecosystem. It also has financial benefits in terms of saving energy and feedstock costs for production.

Suppose that any recycling ratio above τ_c=67% (exemplary values from industry) is sustainable. Since Hanwha's recycle ratio has steadily increased over the years, the undesirable threshold is its value from 2000 (υ_c=32%).

6) *Percent waste to landfill (% of total)* directly measures what fraction of total waste generated gets dumped into landfills. Landfills have many environmental problems such as toxic gas/chemical releases into the air and potential emission of leachate and contaminated water run-off to watercourses and groundwater, deteriorating the health of the surrounding ecosystem as a whole. It also consumes large acres of land that could be utilized for other more productive socioeconomic purposes.

Any value below the average value of other industry leaders (LG and Dow), T_c=20%, is considered sustainable with value 1, and sustainability decreases linearly to Hanwha's all-time high over the last 10 years, U_c=55%.

WATER

7) *Total water consumption* (metric tons per ton of product) measures the amount of freshwater the company uses for its production. Clean freshwater is becoming increasingly scarce and can impact production processes that rely on large volumes of water. The reduction of water consumption through reuse and recycling can contribute to local, national, or regional goal for managing water supplies, and decrease potential pollution caused by the company on consumed water. Water consumption is listed on the GRI reporting guidelines as EN9.

I set the target water consumption level to Hanwha's all-time low T_c=2.51 tons per ton of product and the threshold unsustainable value to the average of other companies (LG, Dow, and BASF), U_c=61.

8) *Chemical Oxygen Demand (COD) emissions* (metric tons per ton of product) measure the amount of pollution in wastewater the company releases. Since a major objective of conventional wastewater treatment is to reduce the chemical/biochemical oxygen demand, COD emissions are an indication of how rigorous the company is in treating wastewater prior to discharging it into the environment. The higher the COD emissions, the more pollution the company causes to water quality.

Lower COD emissions is better, so the target is set to the 10% of the current value, T_c=0.001 tons per ton product, and the lower unsustainable value to the maximum over all companies (BASF; U_c=0.274).

9) *Wastewater emissions* (metric tons per ton of product) are another measure of how efficient the company is in its water consumption. Lower wastewater emissions with respect to the total water consumption indicate higher rates of in-process recycling of water, which overall contribute to reduced impact on freshwater quality.

   The target value is the minimum over all companies (LG) at T_c=0.1 tons per ton product, and the unsustainable threshold value is the average of other companies (Dow and BASF) at Uc=6.9.

POLIC

10) *Community service participation* (hours per employee per year) indicates the company's degree of involvement in community welfare. In addition to financial contributions, promoting volunteer work among its employees not only benefits the society but enhances the company's relations with its surrounding communities.

    It is assumed that no company initiated volunteer work (υ_c=0 hours per employee per year) is not sustainable and that sustainability increases linearly to one at τ_c=18, which is the corporate target since 2007.

11) *Financial contributions to communities* (percent of annual sales) are another measure of the company's benefit to society. They are a useful metric of how dedicated the company is to improving the human system within which it operates.[i] Corporate contributions–such as donations to children outreach programs, cultural events, or community repair–lessen the government's burden on providing for public well-being.

    Similarly as the above indicator (10), it is assumed that the case of no financial contribution to society, υ_c=0%, is considered not sustainable and that sustainability increases linearly to one at τ_c=0.16%, the value that places the average of other companies (LG, SK, Dow and BASF) at the 50% percentile).

12) *Female employee ratio* (%) provides a quantitative measure of diversity within the company. A sustainable organization must ensure equal opportunity for all employees regardless of gender or background. Manufacturing companies, such as Hanwha Chemical, however, due to its labor characteristics, tend to have significantly higher percentage of male employees. The organization must strive to achieve a near equal percentage of both genders, at least for the professional (non-operators) positions. This indicator is recommended to be reported by the GRI initiative (LA13).

    Female employee ratio should not be too low or too high. I have chosen the minimum value for full sustainability as τ_c=23%, which is the value when half of professional employees are female (excluding process operators). Sustainability is 1 from this value up to T_c=50%, when half of *all* employees are female. Sustainability is zero at/below υ_c=4.0% (Hanwha's first reported female ratio in 2004) and is also zero at U_c=100%, when all employees are female.

13) *Average employee tenure* (years) is an indication of employee loyalty to the company, which in turn implies how well the company treats its people by providing good benefits, compensation, work environment, etc. High employee tenure ensures enhanced productivity based on retaining human resources and employee expertise, and also has cost implications in terms of reduced expenses for recruitment of workers and trainings for new-hires.

It is assumed that υ_c=5 years, the minimum in all manufacturing sectors, and τ_c=20, the maximum over all chemical companies in Korea.

WEALTH

14) *Revenue per employee* ($ millions per employee per year) measure the company's economic efficiency. Higher revenue-per-employee indicates that the company can operate on low overhead costs, and therefore do more with fewer employees, which often translates into healthy profits.[iv] The Fortune 500 chemical companies have an average revenue-per-employee of $0.5 million.[v]

It is assumed that any value below υ_c=$0.5 million per employee, the average of the US chemical industry, is not sustainable at 0, and sustainability improves linearly up to τ_c=1.86, the maximum over all investigated companies.

15) *Return on equity* (%) is the amount of net income returned as a percentage of shareholders equity.[vi] It measures the company's profitability by revealing how much profit is generated with the money shareholders have invested. The diversified chemicals sector has an average ROE of 14.5%,[vii] and the company should have a comparable or higher ROE to be economically robust or sustainable.

Any ROE value below υ_c=11.4%, the average ROE of the total US market, is considered unsustainable. Sustainability then improves linearly up to τ_c=23.2%, which is the average over the high-performing companies within this investigation (LG, SK, Eastman, Praxair, and DuPont).

HEALTH

16) *Accident rate* (%) is the ratio of number of injured workers to the total number of workers each year and is a key measure of the company's health and safety performance. Low accident/injury rates are generally linked to positive trends in staff morale and productivity. Fewer injuries also mean lower insurance costs, less health care liability, and lower risk of fines or regulations due to unsafe practices.[i]

I assume that the only fully sustainable value is having no accidents at all, i.e. T_c=0%. Any value above zero is less sustainable up to the 5-year average value within the petrochemical industry in Korea.

17) *Process Safety Management (PSM) grade* (between 0 and 100) is a certification rating all eligible manufacturing facilities must obtain from KOSHA (Korea Occupational Safety and Health Agency) based upon their process safety reports and site inspections. PSM is a quantitative risk management system that requires workplaces operating hazardous facilities/substances to comply with strict safety measures. Grades above 80 are passing, and ones above 90 are approved as sustainable.[viii]

Any grade below υ_c=80 is considered unsustainable. The only fully sustainable value is achieving the highest possible grade, τ_c=100.

18) *R&D expenditures* (% of sales) indicate the company's commitment on developing new technologies to improve and expand its product portfolio. A sustainable corporation must constantly strive for growth by developing new processes or reducing costs by making existing processes more efficient.

R&D expenditures below υ_c=0.3% of sales, the lowest value of all manufacturing industries (that is of petroleum/energy sector), are considered unsustainable. The target value is set at τ_c=3.0%, which is the average over other leading companies (LG, SK, Dow, BASF, and DuPont).

19) *Employee education expenses* (% of sales) shows how dedicated the company is in enhancing the intellectual competence of its employees. Increased employee training/education is generally linked to higher productivity and decreased occurrences of safety related incidents.

Higher education expenses are always better, and the lower threshold value for sustainability of one is set as τ_c=0.32% of net sales, which is the maximum among other companies (BASF). Any value below the minimum value among investigated companies, i.e. υ_c=0.05%, is considered to have zero sustainability.

20) *Employee education duration* (hours per employee per year) is an indication of how much actual training time employees receive as a result of the company's investment in education. Similarly to the above indicator, the more workers are trained, the more focused they will be on increasing the productivity of the company.

The target value for this indicator is set as the value that places the average of other companies at the 50% percentile, i.e. τ_c=45 hours per employee per year. Any value below υ_c=25 hours is considered unsustainable.

(1-2) FUZZIFICATION OF BASIC INDICATORS

The basic indicators explained above come in a variety of scales and units, and lower values mean better sustainability for some indicators but worse for others. To make indicators comparable for further analysis, the data are normalized on a 0-1 scale by assigning 0 to the least desirable indicator values and 1 to the most desirable indicator values or targets, based on industry standards, regulations, comparison with other similar companies, etc.

To make comparisons with Hanwha, I collected basic indicator data on other similar companies in the diversified chemicals sector, namely LG Chemical, SK Innovation (Korea), BASF (Germany), Dow Chemical, Eastman Chemical, and DuPont (USA), when available. I tried to base my selection of critical threshold and target values on data on at least three or more companies.

For example, GHG emissions per ton of product had the maximum value of 0.90 tons CO_2-eq per ton of product over the selected five companies in 2010 (Table 1). This value is set as the least desirable value, U.

Hanwha	LG	Dow	BASF	Eastman
0.47	0.49	0.67	0.77	*0.90*

Table 1 GHG emissions intensity in 2010 (tons CO2-eq per ton of product)

Table 2 shows Hanwha's GHG emissions intensity over the 11-year period starting from 2000. The lowest or most sustainable GHG emissions intensity was achieved in 2006 at the value of 0.37. As this all-time low value also coincides with the corporate goal to reduce GHG emissions by 20% from year 2010, it was set as the target, T.

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
GHG emissions	0.54	0.51	0.49	0.48	0.47	0.43	0.37	-	0.41	0.44	0.47

Table 2 Hanwha's data on GHG emissions intensity from 2000 to 2010 (tons CO2-eq per ton of product)

I used the normalization method by linear interpolation. Since GHG emissions is the "smaller is better" (SB) type, the following normalization curve (Figure 2) is used.

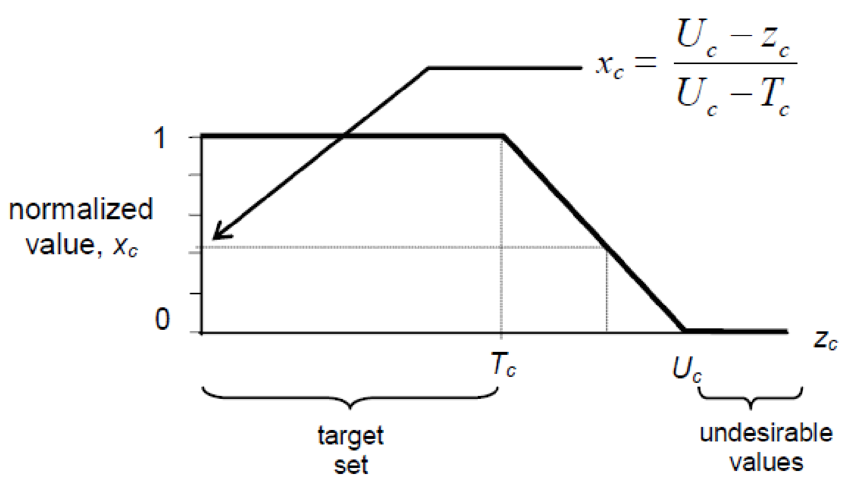


Figure 2 Normalization by linear interpolation: smaller is better (SB)**Error! Bookmark not defined.**

The normalization curve for the GHG emissions indicator with U = 0.37 and T = 0.9 tons CO_2-eq per ton of product is shown below.

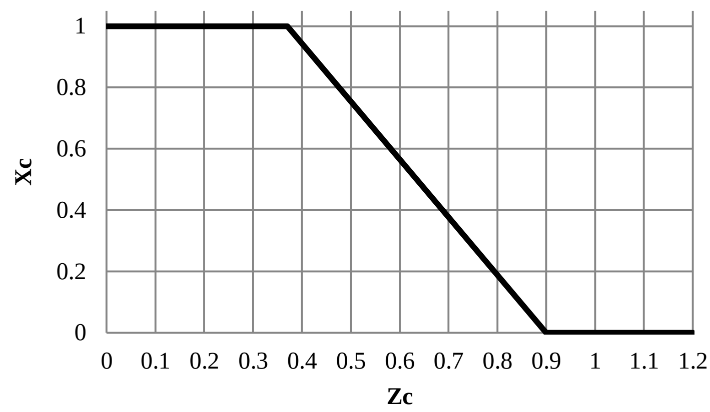


Figure 3 Normalization curve for GHG emissions

For any indicator *c*, let z_c be its value for the company under study. For small-is-better type indicators, the normalized value of the company data, x_c, can be obtained from the following equation:

$$x_c = \frac{U_c - z_c}{U_c - T_c} \qquad (SB\ \text{type})$$

Since GHG emissions is a value that a company continuously strives to reduce over time due to environmental regulations, and such a trend is generally visible in Hanwha's data (Appendix raw data, 2000 to 2010), I took the average of the most recent three years' values (2008-2010) as the company's value, which was then normalized. According to the above equation, the normalized value of Hanwha's GHG emissions per ton of product was

$$x_{GHG} = \frac{0.9 - 0.44}{0.9 - 0.37} = \mathbf{0.87}$$

All other basic indicators were normalized in a similar manner based on relevant critical threshold and target values as shown in Table 3. Calculations for one basic indicator for each secondary indicator are shown in the Appendix. Also shown in the Appendix is a sample calculation of exponential smoothing of data points over multiple years, which was done for relevant indicators.

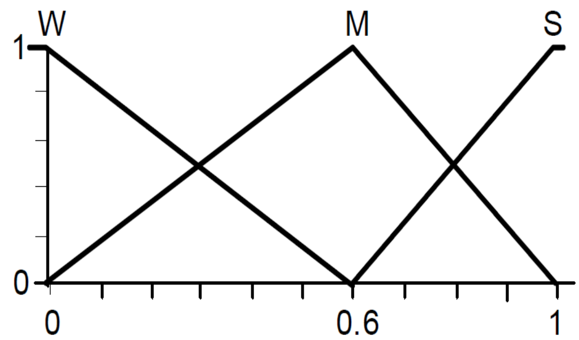
Table 3 Target and least desirable values for the indicators, and their normalized values for Hanwha Chemical

	#	Indicator	Type	Values		Explanation for least and most desirable and threshold values	z_c	Basis	x_c
AIR	1	GHG emissions (CO_2-eq tons per ton product)	SB	T_c	0.37	T is Hanwha's corporate goal to reduce GHG by 20% from 2010.	0.44	3-yr avg (2008-2010)	0.868
				U_c	0.9	U is the maximum over all investigated companies (Eastman).			
	2	SOx, NOx, and dust emissions (kg per ton product)	SB	T_c	0.001	T is 10% of Hanwha's current value.	0.013	3-yr avg (2008-2010)	0.966
				U_c	0.35	U is the average over two global companies that have comparatively large emissions (Dow and BASF).			
	3	Energy consumption (kJ per ton product)	SB	T_c	7.41	T is Hanwha's all time low over the last 10 years (2007).	7.91	3-yr avg (2008-2010)	0.821
				U_c	10.2	U is the average over two global companies that have comparatively large intensities (Dow and Eastman).			
LAND	4	Total waste generation (tons per ton product)	SB	T_c	7.13	T is Hanwha's all-time low over the last 10 years (2009).	8.08	Smoothed over 11 yrs (2000-2010)	0.946
				U_c	24.6	U is the maximum over all companies (Dow).			
	5	% Waste recycled	LB	υ_c	32	υ is Hanwha's value in 2000.	41	3-yr avg (2008-2010)	0.257
				τ_c	67	τ is the average of other exemplary companies (LG and SK).			
	6	% Waste to landfill	SB	T_c	20	T is the average of industry leaders (LG and Dow).	51	3-yr avg (2008-2010)	0.114
				U_c	55	U is Hanwha's all-time high over the last 10 years (2004).			
WATER	7	Water use (tons per ton product)	SB	T_c	2.51	T is Hanwha's all-time low over the last 10 years (2005).	2.6	Smoothed over 11 yrs (2000-2010)	0.998
				U_c	61	U is the average of other companies (LG, Dow and BASF).			
	8	COD emissions (tons per ton product)	SB	T_c	0.001	T is 10% of Hanwha's current value.	0.011	3-yr avg (2008-2010)	0.963
				U_c	0.274	U is the highest of the companies for which the data was obtained (BASF).			
	9	Wastewater generation (tons per ton product)	SB	T_c	0.1	T is the minimum over all investigated companies (LG).	1.0	Smoothed over 10 yrs (2001-2010)	0.868
				U_c	6.9	U is the average of other companies (Dow and BASF).			

POLIC	10	Community service (hours per employee per year)	LB	υ_c	0	υ is the case of no corporate initiated community service.	17	3-yr avg (2008-2010)	0.944
				τ_c	18	τ is Hanwha's corporate target initiated in 2007.			
	11	Contributions as a percent of net sales (%)	LB	υ_c	0	υ is the case of no financial contribution to society.	0.12	3-yr avg (2008-2010)	0.750
				τ_c	0.16	τ is the value that places the average of other companies (LG, SK, Dow, and BASF) at the 50% percentile.			
	12	Female employee ratio (%)	NB	υ_c	4.0	υ is Hanwha's value in 2004 (first reported female ratio).	10	2010	0.316
				τ_c	23	τ is the value assuming half of professional employees were females (excluding process operators).			
				T_c	50	T is the value assuming half of all employees were female (including process operators).			
				U_c	100	U is when all employees were female.			
	13	Average employee tenure (years)	LB	υ_c	5	υ is the minimum in all manufacturing sectors.[a]	14.2	3-yr avg (2008-2010)	0.613
				τ_c	20	τ is the maximum over all Chemical companies in Korea.[b]			
WEALTH	14	Revenue per employee ($ millions per employee)	LB	υ_c	0.5	υ is the average of chemicals industry (USA).[c]	1.4	3-yr avg (2008-2010)	0.662
				τ_c	1.86	τ is the maximum over all investigated companies (LG)			
	15	Return on Equity (%)	LB	υ_c	11.4	υ is the average ROE of total market.[d]	15.9	Smoothed over 8 yrs (2003-2010)	0.381
				τ_c	23.2	τ is the average of high-performing chemical companies (LG, SK, Eastman, Praxair, DuPont).[e]			
HEALTH	16	Injury rate (%)	SB	T_c	0	T is zero accidents.	0.026	Smoothed over 6 yrs (2005-2010)	0.961
				U_c	0.675	U is the 5-yr avg of Korean petrochemical industry.[f]			
	17	Process safety management (PSM) grade (0-100)	LB	υ_c	80	υ is the satisfactory grade.	97	2010 [g]	0.850
				τ_c	100	τ is the highest possible grade.			
KNOW	18	R&D Expenditures as a percent of net sales (%)	LB	υ_c	0.3	υ is the lowest of all manufacturing industries (Petroleum/Energy).[h]	1.1	3-yr avg (2008-2010)	0.296
				τ_c	3.0	τ is the average of other companies (LG, SK, Dow, BASF, and DuPont).			
	19	Employee education expenses as a percent of net sales (%)	LB	υ_c	0.05	υ is the minimum among other companies (LG).	0.09	3-yr avg (2008-2010)	0.148
				τ_c	0.32	τ is the maximum among other companies (BASF).			
	20	Employee education (hours per employee per year)	LB	υ_c	25	υ is Hanwha's value in 2003.	77.7	3-yr avg (2008-2010)	1.000
				τ_c	45	τ is the value that places the average of other companies (SK, Dow, and BASF) at the 50% percentile.			

[a] Employee tenure data (US Bureau of Labor Statistics, 2010): http://www.bls.gov/news.release/pdf/tenure.pdf
[b] Employee tenure data (Korean chemical industry,2011): http://blog.naver.com/PostView.nhn?blogId=naamoo01&logNo=130110903305
[c] Revenue per employee (Fortune 500 companies, CNN): http://money.cnn.com/magazines/fortune/fortune500/2007/performers/industries/revenues_per_employee/index.html
[d] ROE data (NYU Stern, 2011): http://pages.stern.nyu.edu/~adamodar/New_Home_Page/datafile/roe.html
[e] Corporate financial summary (Naver finance): http://finance.naver.com/item/coinfo.nhn?code=009830
[f] Accident rate in Korean industries (The Korea Occupational Safety and Health Agency): www.kosha.or.kr
[g] Hanwha received a score >90 since 1996
[h] "Industrial R&D as a Percent of Net Sales: 2007." *Nsf.gov*. NSF's Industrial Research and Development Information System. Web. 04 Mar. 2012. <http://www.nsf.gov/statistics/iris/search_hist.cfm?indx=7>.

A fuzzy assessment of sustainability involves fuzzy inputs and outputs. This requires fuzzification of the normalized basic indicators. When converting between crisp and fuzzy sets, we use membership functions of different set of linguistic variables. I fuzzified the basic indicators using the WMS (weak, medium, and strong), for which membership functions are shown in Figure 4.



For $0 \leq x \leq 0.6$,

$$\mu_W(x) = \frac{0.6 - x}{0.6};\ \mu_M(x) = \frac{x}{0.6}$$

For $0.6 < x \leq 1.0$,

$$\mu_M(x) = \frac{1 - x}{0.4};\ \mu_S(x) = \frac{x - 0.6}{0.4}$$

Figure 4 Membership functions for the WMS fuzzy sets

The GHG emissions indicator has a normalized value of x=0.868, which lies above 0.6. Thus, its fuzzy set is:

$$\mu_M(x) = \frac{1 - 0.868}{0.4} = 0.33$$

and

$$\mu_S(x) = \frac{0.868 - 0.6}{0.4} = 0.67$$

Likewise, all the rest of the normalized values of the basic indicators are fuzzified (See Appendix) and presented in Table 4.

Table 4 Fuzzification of basic inputs

	#	Indicator	x_c	Fuzzy set		
				W	M	S
AIR	1	GHG emissions intensity	0.868	0	0.33	0.67
	2	SOx, NOx, and dust combined emissions intensity	0.966	0	0.09	0.91
	3	Energy intensity	0.821	0	0.45	0.55
LAND	4	Total waste intensity	0.946	0	0.14	0.86
	5	Waste recycling rate	0.257	0.57	0.43	0
	6	% Waste to landfill	0.114	0.81	0.19	0
WATER	7	Water use intensity	0.998	0	0.00	1.00
	8	COD intensity	0.963	0	0.09	0.91
	9	Wastewater intensity	0.868	0	0.33	0.67
POLIC	10	Community service	0.944	0	0.14	0.86
	11	Donations as a percent of net sales	0.750	0	0.63	0.38
	12	Female employee ratio	0.316	0.47	0.53	0
	13	Average employee tenure	0.613	0	0.97	0.03
WEALTH	14	Revenue per employee	0.662	0	0.85	0.15
	15	ROE	0.381	0.36	0.64	0
HEALTH	16	Accident rate	0.961	0	0.10	0.90
	17	Process safety management (PSM) grade	0.850	0	0.38	0.63
KNOW	18	R&D Expenditures as a percent of net sales	0.296	0.51	0.49	0
	19	Employee education/training expenses as a percent of net sales	0.148	0.75	0.25	0
	20	Employee education/training (hours per employee per year)	1.000	0	0	1.00

(2-1) SECONDARY INDICATORS – RULE BASE FIRING

The fuzzy values of the basic indicators then serve as inputs to a rule base that contains "if-then" rules relating output to input linguistic values. This mechanism is called an inference engine whose fuzzy output is represented by the membership grades to which the output belongs to the corresponding linguistic values. In a Takagi-Sugeno-Kang (TSK) fuzzy system, like ours, the output membership grade of a rule-firing is the product of its input membership grades.

For example, the secondary indicator LAND is composed of three basic indicators, (1) total waste generation, (2) waste recycling rate, and (3) % waste to landfill. I constructed the following rule base to reflect the most impact "Total waste generation" has on LAND (most weight is placed on that indicator). The rule base is also slightly pessimistic, meaning it is harder to get positive grades than negative ones.

As shown below (Table 5), Rules 10, 11, 13, 14, 19, 20, 22 and 23 fire based on the fuzzy input set of:

Total waste generation	M(0.14) and S(0.86)
Waste recycling rate	W(0.57) and M(0.43)
% Waste to landfill	W(0.81) and M(0.19)

Table 5 LAND rule base

Rule #	*If*	*Total waste generation*	*AND*	*Waste recycling rate*	*AND*	*% Waste to landfill*	*THEN*	*LAND*
1		W		W		W		VB
2		W		W		M		VB
3		W		W		S		B
4		W		M		W		B
5		W		M		M		B
6		W		M		S		B
7		W		S		W		B
8		W		S		M		A
9		W		S		S		A
10		**M (0.14)**		**W (0.57)**		**W (0.81)**		**B (0.14×0.57×0.81=0.06)**
11		**M (0.14)**		**W (0.57)**		**M (0.19)**		**A (0.14×0.57×0.19=0.01)**
12		M		W		S		A
13		**M (0.14)**		**M (0.43)**		**W (0.81)**		**A (0.14×0.43×0.81=0.05)**
14		**M (0.14)**		**M (0.43)**		**M (0.19)**		**A (0.14×0.43×0.19=0.01)**
15		M		M		S		A
16		M		S		W		A
17		M		S		M		A

18	M	S	S	G
19	**S (0.96)**	**W (0.57)**	**W (0.81)**	**B (0.96×0.57×0.81=0.40)**
20	**S (0.96)**	**W (0.57)**	**M (0.19)**	**A (0.96×0.57×0.19=0.09)**
21	S	W	S	A
22	**S (0.96)**	**M (0.43)**	**W (0.81)**	**A (0.96×0.43×0.81=0.30)**
23	**S (0.96)**	**M (0.43)**	**M (0.19)**	**G (0.96×0.43×0.19=0.07)**
24	S	M	S	G
25	S	S	W	G
26	S	S	M	G
27	S	S	S	VG

Following the individual rule-firings, the output linguistic variables and the corresponding membership grades are summed to yield the fuzzy value of LAND:

$$\begin{aligned} \mathrm{B}(0.06+0.40) &= \mathbf{B(0.46)} \\ \mathrm{A}(0.01+0.05+0.01+0.09+0.30) &= \mathbf{A(0.47)} \\ \mathrm{G}(0.07) &= \mathbf{G(0.07)} \end{aligned}$$

(2-2) DEFUZZIFICATION

The fuzzy values can be converted to crisp values by means of defuzzification. I performed singleton or height defuzzification, where

$$x_{crisp} = \frac{\sum_{i=lin.var.}(PV)_i \mu_i}{\sum_{i=lin.var.} \mu_i}$$

$$\text{where } (PV)_i = \text{peak value of linguistic variable i}$$

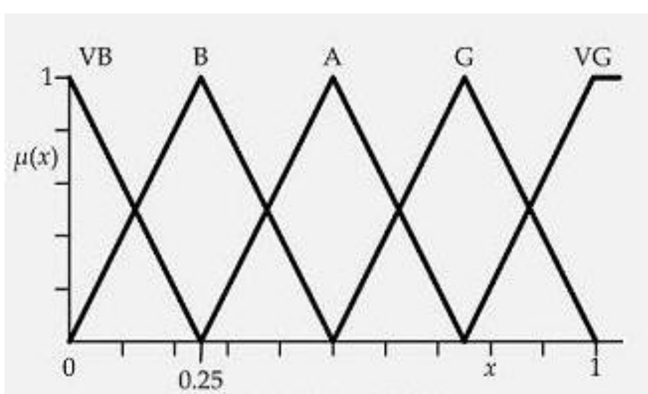


Figure 5 Membership functions for the VBBAGVG fuzzy sets [i]

The VBBAGVG linguistic variables have peak values between 0 and 1.0 at increments of 0.25 (Figure 5). Thus, the crisp value of LAND is:

$$x_{LAND} = \frac{(PV)_B \mu_B + (PV)_A \mu_A + (PV)_G \mu_G}{\mu_B + \mu_A + \mu_G}$$

$$= \frac{0.25(0.46) + 0.5(0.47) + 0.75(0.07)}{0.46 + 0.47 + 0.07} = \mathbf{0.40}$$

The crisp values of the other secondary indicators were computed similarly (Table 6) using the rule bases presented in Appendix.

Secondary indicator	Fuzzy value	Crisp value
AIR	A (0.33) G (0.33) VG (0.34)	0.75
LAND	B(0.46) A(0.47) G(0.07)	0.40
WATER	G(0.39) VG(0.61)	0.90
POLIC	B(0.36) A(0.46) G(0.18) VG(0.01)	0.46
WEALTH	B(0.31) A(0.59) G(0.10)	0.45
HEALTH	A (0.04) G (0.40) VG (0.56)	0.88
KNOW	B(0.88) A(0.12)	0.28

Table 6 Fuzzy and crisp values of all secondary indicators

(3) PRIMARY INDICATOR

The inference engines for ECOS and HUMS consist of a rule base with $5^3 = 125$ rules and $5^4 = 625$ rules because they have three and four inputs, respectively, each with five linguistic variables (VB, B, A, G, and VG). To express their rule bases in a more compact manner, I used the "SUM" notation.

I would like AIR to weigh twice as much as LAND and WATER because there has been an ever-increasing focus on a global, national, and corporate level on reducing air emissions such as greenhouse gases due to climate concerns, and Hanwha's environmental footprint in land and water integrity have been steady over the years of this study.

Let $\mathrm{SUM} = \mathrm{L_{AIR}} + \mathrm{L_{LAND}} + \mathrm{L_{WATER}}$

where $\mathrm{L_{AIR}} = \{0 = \mathrm{VB}, 2 = \mathrm{B}, 4 = \mathrm{A}, 6 = \mathrm{G}, 8 = \mathrm{VG}\}$

$\mathrm{L_{LAND\ or\ WATER}} = \{0 = \mathrm{VB}, 1 = \mathrm{B}, 2 = \mathrm{A}, 3 = \mathrm{G}, 4 = \mathrm{VG}\}$

For each combination of inputs, I calculated SUM and determine the linguistic value of ECOS based on the following rule base, which I constructed to be slightly pessimistic:

$$\mathrm{ECOS} = \begin{cases} \mathrm{VB}; & 0 \leq \mathrm{SUM} \leq 3 \\ \mathrm{B}; & 4 \leq \mathrm{SUM} \leq 7 \\ \mathrm{A}; & 8 \leq \mathrm{SUM} \leq 11 \\ \mathrm{G}; & 12 \leq \mathrm{SUM} \leq 14 \\ \mathrm{VG}; & 15 \leq \mathrm{SUM} \leq 16 \end{cases}$$

The fuzzy value of ECOS was computed as outlined in Table 7.

Table 7 Rules that fire in calculating ECOS

Rule	*If* AIR *is*		*and* LAND *is*		*and* WATER *is*		L_{AIR}	L_{LAND}	L_{WATER}	SUM	*Then* ECOS	
1	A	0.33	B	0.46	G	0.39	4	1	3	8	A	0.0600
2	A	0.33	B	0.46	VG	0.61	4	1	4	9	A	0.0925
3	A	0.33	A	0.47	G	0.39	4	2	3	9	A	0.0606
4	A	0.33	A	0.47	VG	0.61	4	2	4	10	A	0.0933
5	A	0.33	G	0.07	G	0.39	4	3	3	10	A	0.0092
6	A	0.33	G	0.07	VG	0.61	4	3	4	11	A	0.0141
7	G	0.33	B	0.46	G	0.39	6	1	3	10	A	0.0603
8	G	0.33	B	0.46	VG	0.61	6	1	4	11	A	0.0930
9	G	0.33	A	0.47	G	0.39	6	2	3	11	A	0.0609

10	G	0.33	A	0.47	VG	0.61	6	2	4	12	G	0.0938
11	G	0.33	G	0.07	G	0.39	6	3	3	12	G	0.0092
12	G	0.33	G	0.07	VG	0.61	6	3	4	13	G	0.0142
13	VG	0.34	B	0.46	G	0.39	8	1	3	12	G	0.0614
14	VG	0.34	B	0.46	VG	0.61	8	1	4	13	G	0.0947
15	VG	0.34	A	0.47	G	0.39	8	2	3	13	G	0.0620
16	VG	0.34	A	0.47	VG	0.61	8	2	4	14	G	0.0955
17	VG	0.34	G	0.07	G	0.39	8	3	3	14	G	0.0094
18	VG	0.34	G	0.07	VG	0.61	8	3	4	15	VG	0.0144

Summing the outputs from individual rule-firings, the fuzzy value of ECOS was computed to be **A(0.55), B(0.44) and VG(0.01)**, which corresponds to a crisp value of **0.617** after defuzzification (refer to "*Defuzzification to obtain a crisp value"* section for the formula).

The fuzzy sets of HUMS are determined similarly but with a twofold weight on POLIC because it has the most number of basic indicators (four as opposed to two for HEALH and WEALTH and three for KNOW), which seem to be significant indicators of the company's impact on its employees and communities.

Let $\text{SUM} = \text{L}_{\text{POLIC}} + \text{L}_{\text{WEALTH}} + \text{L}_{\text{HEALTH}} + \text{L}_{\text{KNOW}}$

$$\text{where} \qquad \text{L}_{\text{POLIC}} = \{0 = \text{VB}, 2 = \text{B}, 4 = \text{A}, 6 = \text{G}, 8 = \text{VG}\}$$
$$\text{L}_{\text{others}} = \{0 = \text{VB}, 1 = \text{B}, 2 = \text{A}, 3 = \text{G}, 4 = \text{VG}\}$$

and

$$\text{HUMS} = \begin{cases} \text{VB}; & 0 \le \text{SUM} \le 4 \\ \text{B}; & 5 \le \text{SUM} \le 8 \\ \text{A}; & 9 \le \text{SUM} \le 12 \\ \text{G}; & 13 \le \text{SUM} \le 16 \\ \text{VG}; & 17 \le \text{SUM} \le 20 \end{cases}$$

From this slightly pessimistic rule base, a total of 72 rules fired; the fuzzy value of HUMS was **B(0.19), A(0.72), and G(0.09)**, which corresponds to **0.476**.

(4) OVERALL SUSTAINABILITY (OSUS)

Finally, the two primary indicators, ECOS and HUMS, were combined to yield overall sustainability, OSUS. I placed equal weights on ECOS and HUMS to appropriately reflect Hanwha's impact on both the environment, as a production facility, and its society, as an employer and a corporate citizen.

Let $\mathrm{SUM} = \mathrm{L_{ECOS}} + \mathrm{L_{HUMS}}$, where $\mathrm{L_i} = \{0 = \mathrm{VB}, 1 = \mathrm{B}, 2 = \mathrm{A}, 3 = \mathrm{G}, 4 = \mathrm{VG}\}$.

Since OSUS uses the ELVLLFLIFHHVHEH linguistic values, the range of possible SUM values were distributed evenly:

$$\mathrm{OSUS} = \begin{cases} \mathrm{EL} & \mathrm{SUM} = 0 \\ \mathrm{VL} & \mathrm{SUM} = 1 \\ \mathrm{L} & \mathrm{SUM} = 2 \\ \mathrm{FL} & \mathrm{SUM} = 3 \\ \mathrm{I} & \mathrm{SUM} = 4 \\ \mathrm{FH} & \mathrm{SUM} = 5 \\ \mathrm{H} & \mathrm{SUM} = 6 \\ \mathrm{VH} & \mathrm{SUM} = 7 \\ \mathrm{EH} & \mathrm{SUM} = 8 \end{cases}$$

Based on the above rule base, the fuzzy value of OSUS was calculated (Table 8).

Table 8 Rules that fire in calculating OSUS

Rule	μ_{ECOS}		μ_{HUMS}		L_{ECOS}	L_{HUMS}	SUM	OSUS ($\mu_{ECOS} \times \mu_{HUMS}$)	
1	A	0.55	B	0.19	2	1	3	FL	0.1450
2	A	0.55	A	0.72	2	2	4	I	0. 3960
3	A	0.55	G	0.09	2	3	5	FH	0.0495
4	G	0.44	B	0.19	3	1	4	I	0.0836
5	G	0.44	A	0.72	3	2	5	FH	0.3168
6	G	0.44	G	0.09	3	3	6	H	0.0396
7	VG	0.01	B	0.19	4	1	5	FH	0.0019
8	VG	0.01	A	0.72	4	2	6	H	0.0072
9	VG	0.01	G	0.09	4	3	7	VH	0.0009

The fuzzy value of OSUS was computed to be **FL(0.10), I(0.47), FH(0.37)** and **H(0.05)** from summing all individual rule-firing outputs. The final, crisp value for OSUS was obtained using height defuzzification:

$$x_{OSUS} = \frac{(PV)_{FL}\mu_{FL} + (PV)_{I}\mu_{I} + (PV)_{FH}\mu_{FH} + (PV)_{H}\mu_{H}}{\mu_{FL} + \mu_{I} + \mu_{FH} + \mu_{H}}$$

where the peak values of the linguistic values are obtained from (Figure 6):

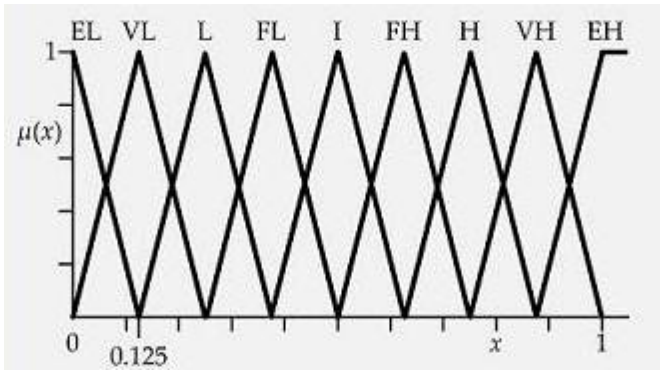


Figure 6 Membership functions for the ELVLLFLIFHHVHEH fuzzy sets **Error! Bookmark not defined.**

The crisp value for Hanwha's overall sustainability was computed as:

$$x_{OSUS} = \frac{0.375(0.10) + 0.5(0.47) + 0.625(0.37) + 0.75(0.05)}{0.10 + 0.47 + 0.37 + 0.05} = \mathbf{0.547}$$

Results

I found the overall sustainability of Hanwha Chemical to be 0.55 on a scale from 0 to 1. Although the number is not a stand-alone objective measure of the company's sustainability, it gives an indication of how it compares with respect to other companies in the chemicals sector because the model inherently operates by comparing its values to others' (via normalization). I used the identical model to evaluate the OSUS of other chemical companies, of which results are shown in Table 9:

	Hanwha	*LG Chem*	*BASF*	*Dow*
ECOS	0.62	0.66	0.10	0.18
HUMS	0.48	0.34	0.40	0.29
OSUS	**0.55**	**0.50**	**0.25**	**0.23**

Table 9 OSUS of other companies using the model

Hanwha received the highest sustainability index among the four companies. LG Chemical performed slightly better in the environmental aspect while moderately worse in the human dimension, resulting in a marginally lower OSUS of 0.50. The two global chemical companies, BASF and Dow, however, received significantly inferior scores compared to the two Korean companies on this particular SAFE model. Their unsatisfactory performance owes greatly to their weak environmental responsibility. Based on the result, I conclude that Hanwha Chemical is average (I–intermediate) or fairly sustainable (FL–fairly high) with respect to the leading industry standard, but performs superior to other major global chemical companies.

The table below, Table 10, compiles all the crisp values starting from the basic indicators to the final overall sustainability indicator, and all the intermediate values of Hanwha. Between the two primary indicators, Hanwha performs worse on the human system dimension. This is largely because it performed poorly in the knowledge/education function, specifically by making insufficient investments in R&D and employee education. The company should consider expanding its R&D and education budget to strengthen its product portfolio and process efficiencies for sustainable growth. Also, the company's satisfactory score on employee education *time* as opposed to education *expenses* implies that the current education/training system for employees might be somewhat rudimentary or lacking in cutting-edge technologies (thus the low cost of trainings).

Overall	Primary indicators	Secondary indicators		Basic indicators	
OSUS 0.55	ECOS 0.62	AIR	0.75	GHG emissions	0.87
				SOx, NOx, and dust emissions	0.97
				Energy consumption	0.82
		LAND	0.40	Total waste generation	0.95
				Waste recycling rate	0.26
				% Waste to landfill	0.11
		WATER	0.90	Water use	1.00
				COD intensity	0.96
				Wastewater discharge	0.87
	HUMS 0.48	POLIC	0.46	Community service	0.94
				Donations	0.75
				Female employee ratio	0.32
				Average employee tenure	0.61
		WEALTH	0.45	Revenue per employee	0.66
				Return on equity	0.38
		HEALTH	0.88	Accident rate	0.96
				PSM grade	0.85
		KNOW	0.28	R&D Expenditures	0.30
				Employee education expenses	0.15
				Employee education time	1.00

Table 10 Summary of crisp values for all indicators

The second worst performing secondary indicator is land integrity, which is largely due to Hanwha's low recycling rate and high reliance on landfills as a means of waste disposal. However, because the total waste generation itself is very small in volume (indicated by the normalized value of 0.97), the low recycling rate or high percentage to landfill would have a lesser impact on land integrity than their bad scores might indicate. On the bright side, the company employs highly sustainable practices in preserving air and water integrity and safety/health issues for its employees.

Sensitivity analysis was conducted to determine the effects of changing each of the sustainability indicators on the overall sustainability as shown in Table 11 (See Appendix for a more detailed spreadsheet). The results can be used in determining necessary policies and actions for sustainable development. In my analysis, I increased and decreased Hanwha's input values for the basic indicators by 10% to study their effects on OSUS. The cases that affect OSUS the most are shaded in green, and those that have the least effects are shaded in red. Changes in SO_x/NO_x/dust emissions, waste generation, COD emissions, accident rate, and employee education time had negligible impact on the overall sustainability of Hanwha. The model had the most sensitivity, however, to changes in energy consumption, % waste to landfill, and average employee tenure. Out of these, *decreasing* the dependence on landfill seems most urgent considering its low normalized value along with improving the return on equity.

Basic indicators	x_c	Sensitivity, $\lvert D_c \rvert$	
		-10%	+10%
GHG emissions [ton/ton prod]	0.87	0.0024	0.0024
Air emissions [kg/ton prod]	0.97	0.0000	0.0000
Energy use [GJ/ton prod]	0.82	0.0042	0.0055
Waste generated [ton/ton prod]	0.95	0.0000	0.0000
% waste recycled	0.26	0.0040	0.0039
% waste to landfill	**0.11**	0.0064	0.0050
Water use [ton/ton prod]	1.00	0.0000	0.0000
COD emissions [ton/ton prod]	0.96	0.0000	0.0000
Wastewater discharge [ton/ton prod]	0.87	0.0001	0.0001
Community service [hr/emp/yr]	0.94	0.0006	0.0003
Donations [% of sales]	0.75	0.0028	0.0027
Female %	0.32	0.0035	0.0034
Avg emp tenure [yr]	0.61	0.0030	0.0055
Revenue per emp [mil $/emp]	0.66	0.0024	0.0027
ROE (%)	**0.38**	0.0051	0.0051
Accident Rate[%]	0.96	0.0000	0.0000
PSM grade	0.85	0.0051	0.0021
R&D exp [% of revenue]	0.30	0.0002	0.0004
Education exp [$/emp]	0.15	0.0008	0.0007
Education time [hr/emp]	1.00	0.0000	0.0000

Table 11 Sensitivity analysis (basic indicator inputs were perturbed ±10%)

Appendices

SAMPLE DATA SMOOTHING

Injury rate (%)

	$\beta =$	0.22							
k	t_k	x_k	$t_k - t_{k-1}$	β^(t_k-t_{k-1})	N(k)	D(k)	x(k)	*error* x_k - x(k-1)	*e*^2
1	2005	0.25	-	-	0.250	1.000	0.25	0.2500	0.06250
2	2006	0.21	1	0.22	0.265	1.220	0.22	-0.0400	0.00160
3	2007	0.16	1	0.22	0.218	1.268	0.17	-0.0572	0.00327
4	2008	0.06	1	0.22	0.108	1.279	0.08	-0.1121	0.01257
5	2009	0.13	1	0.22	0.154	1.281	0.12	0.0455	0.00207
6	2010	0.00	1	0.22	0.034	1.282	0.026	-0.1200	0.01440
								SSE	0.096415

$$z_{injury\,rate} = \mathbf{0.026}\,\%$$

BASIC INDICATOR SAMPLE CALCULATION

1) AIR – GHG emissions (shown in *Model Description* section)

2) LAND – Total solid waste generation (tons per ton product)

- ✓ Small-is-better type
- ✓ Target value 7.13 (Hanwha's all-time low over the last 10 years)
- ✓ Undesirable 24.6 (Maximum over all companies – Dow)
- ✓ Hanwha 8.08 (11-year average)

Since $x_c = \frac{U_c - z_c}{U_c - T_c}$ for SB-type normalization curves,

$$x_{\text{Total waste gen.}} = \frac{24.6 - 8.08}{24.6 - 7.13} = \mathbf{0.946}$$

This normalized value is fuzzified as follows:

Since $x_{\text{Total waste gen.}} > 0.6$,

$$\mu_M(x) = \frac{1 - 0.946}{0.4} = 0.14 \quad \text{and} \quad \mu_S(x) = 1 - 0.14 = 0.86$$

$$\therefore \mathbf{M(0.14)\ and\ S(0.86)}$$

3) WATER – Wastewater generation (tons per ton product)

- ✓ Small-is-better type
- ✓ Target value 0.1 (Minimum over all investigated companies – LG)
- ✓ Undesirable 6.9 (Average over other companies – Dow and BASF)
- ✓ Hanwha 1.0 (10-year average)

Since $x_c = \frac{U_c - z_c}{U_c - T_c}$ for SB-type normalization curves,

$$x_{\text{wastewater gen.}} = \frac{6.9 - 1.0}{6.9 - 0.1} = \mathbf{0.868}$$

Since $x_{\text{wastewater gen.}} > 0.6$,

$$\mu_M(x) = \frac{1 - 0.868}{0.4} = 0.33 \quad \text{and} \quad \mu_S(x) = 1 - 0.33 = 0.67$$

$$\therefore \mathbf{M(0.33)\ and\ S(0.67)}$$

4) POLIC – Community service participation (hours per employee per year)

- ✓ Large-is-better type
- ✓ Target value 18 (Hanwha’s corporate target established in 2007)
- ✓ Undesirable 0 (no corporate initiated community service)
- ✓ Hanwha 17 (3-year average)

Since $x_c = \frac{z_c - \upsilon_c}{\tau_c - \upsilon_c}$ for LB-type normalization curves,

$$x_{\text{community serv.}} = \frac{17 - 0}{18 - 0} = \mathbf{0.944}$$

Since $x_{\text{community serv.}} > 0.6$,

$$\mu_M(x) = \frac{1 - 0.944}{0.4} = 0.14 \quad \text{and} \quad \mu_S(x) = 1 - 0.14 = 0.86$$

$$\therefore \mathbf{M(0.14)\ and\ S(0.86)}$$

5) WEALTH – Revenue per employee ($ millions per employee)

- ✓ Large-is-better type
- ✓ Target value 1.86 (Maximum over all investigated companies – LG)
- ✓ Undesirable 0.5 (Average of the chemical industry in the US)
- ✓ Hanwha 1.4 (3-year average)

Since $x_c = \frac{z_c - \upsilon_c}{\tau_c - \upsilon_c}$ for LB-type normalization curves,

$$x_{\text{revenue per emp.}} = \frac{1.4 - 0.5}{1.86 - 0.5} = \mathbf{0.662}$$

Since $x_{\text{revenue per emp.}} > 0.6$,

$$\mu_M(x) = \frac{1 - 0.662}{0.4} = 0.85 \quad \text{and} \quad \mu_S(x) = 1 - 0.85 = 0.15$$

$$\therefore \mathbf{M(0.85)\ and\ S(0.15)}$$

6) HEALTH – Injury rate (%)

- ✓ Small-is-better type
- ✓ Target value 0 (zero accidents)
- ✓ Undesirable 0.675 (5-year average of Korean petrochemical industry)
- ✓ Hanwha 0.135 (6-year average)

Since $x_c = \frac{U_c - z_c}{U_c - T_c}$ for SB-type normalization curves,

$$x_{\text{injury rate}} = \frac{0.675 - 0.135}{0.675 - 0} = \mathbf{0.800}$$

Since $x_{\text{injury rate}} > 0.6$,

$$\mu_M(x) = \frac{1 - 0.80}{0.4} = 0.50 \quad \text{and} \quad \mu_S(x) = 1 - 0.50 = 0.50$$

$$\therefore \mathbf{M(0.50)\ and\ S(0.50)}$$

7) KNOW – R&D expenditures as a percent of sales (%)

- ✓ Large-is-better type
- ✓ Target value 3.0 (Average of other companies – LG, SK, Dow, BASF, and DuPont)
- ✓ Undesirable 0.3 (Minimum over all manufacturing sectors (Petroleum/Energy))
- ✓ Hanwha 1.1 (3-year average)

Since $x_c = \frac{z_c - \upsilon_c}{\tau_c - \upsilon_c}$ for LB-type normalization curves,

$$x_{\text{revenue per emp.}} = \frac{1.1 - 0.3}{3.0 - 0.3} = \mathbf{0.296}$$

Since $x_{\text{revenue per emp.}} < 0.6$,

$$\mu_W(x) = \frac{0.6 - 0.296}{0.6} = 0.51 \quad \text{and} \quad \mu_M(x) = 1 - 0.51 = 0.49$$

$$\therefore \mathbf{W(0.51)\ and\ S(0.49)}$$

SECONDARY INDICATOR RULE BASES

AIR

	If	*GHG emissions*	*AND*	*SOx, NOx, and dust emissions*	*AND*	*Energy intensity*	*THEN*	*AIR*	
1		W		W		W		VB	
2		W		W		M		VB	
3		W		W		S		B	
4		W		M		W		B	
5		W		M		M		B	
6		W		M		S		B	
7		W		S		W		B	
8		W		S		M		B	
9		W		S		S		B	
10		M		W		W		B	
11		M		W		M		B	
12		M		W		S		B	
13		M		M		W		B	
14		**M (0.33)**		**M (0.09)**		**M (0.45)**		**A**	**(0.01)**
15		**M (0.33)**		**M (0.09)**		**S (0.55)**		**A**	**(0.02)**
16		M		S		W		A	
17		**M (0.33)**		**S (0.91)**		**M (0.45)**		**A**	**(0.13)**
18		**M (0.33)**		**S (0.91)**		**S (0.55)**		**A**	**(0.17)**
19		S		W		W		B	
20		S		W		M		A	
21		S		W		S		A	
22		S		M		W		A	
23		**S (0.67)**		**M (0.09)**		**M (0.45)**		**G**	**(0.03)**
24		**S (0.67)**		**M (0.09)**		**S (0.55)**		**G**	**(0.03)**
25		S		S		W		G	
26		**S (0.67)**		**S (0.91)**		**M (0.45)**		**G**	**(0.27)**
27		**S (0.67)**		**S (0.91)**		**S (0.55)**		**VG**	**(0.34)**

WATER

	If	*Water use*	*AND*	*COD emissions*	*AND*	*Wastewater*	*THEN*	*WATER*	
1		W		W		W	3	VB	
2		W		W		M	4	B	
3		W		W		S	5	B	
4		W		M		W	4	B	
5		W		M		M	5	B	
6		W		M		S	6	A	
7		W		S		W	5	B	
8		W		S		M	6	A	
9		W		S		S	7	A	
10		M		W		W	4	B	
11		M		W		M	5	A	
12		M		W		S	6	A	
13		M		M		W	5	B	
14		**M (0)**		**M (0.10)**		**M (0.33)**	**6**	**A**	**(0.00)**
15		**M (0)**		**M (0.10)**		**S (0.67)**	**7**	**A**	**(0.00)**
16		M		S		W	6	A	
17		**M (0)**		**S (0.90)**		**M (0.33)**	**7**	**A**	**(0.00)**
18		**M (0)**		**S (0.90)**		**S (0.67)**	**8**	**G**	**(0.00)**
19		S		W		W	5	B	
20		S		W		M	6	A	
21		S		W		S	7	A	
22		S		M		W	6	A	
23		**S (1)**		**M (0.10)**		**M (0.33)**	**7**	**G**	**(0.03)**
24		**S (1)**		**M (0.10)**		**S (0.67)**	**8**	**G**	**(0.07)**
25		S		S		W	7	G	
26		**S (1)**		**S (0.90)**		**M (0.33)**	**8**	**G**	**(0.30)**
27		**S (1)**		**S (0.90)**		**S (0.67)**	**9**	**VG**	**(0.60)**

POLIC

SUM = L_COMSERV + L_DONATION + L_FEMALE+ L_TENURE

where L_i = {0 = W, 1 = M, 2 = S}

POLIC = VB, $0 \leq SUM \leq 2$

B, $3 \leq SUM \leq 4$

A, SUM = 5

G, SUM = 6

VG, $7 \leq SUM \leq 8$

WEALTH

	If	*RPE*	*AND*	*ROE*	*THEN*	*WEALTH*	
1		W		W			
2		W		M			
3		W		S			
4		**M (0.85)**		**W (0.36)**			**(0.31)**
5		**M (0.85)**		**M (0.64)**			**(0.54)**
6		M		S			
7		**S (0.15)**		**W (0.36)**			**(0.06)**
8		**S (0.15)**		**M (0.64)**			**(0.10)**
9		S		S			

HEALTH

	If	*Accident rate*	*AND*	*PSM grade*	*THEN*	*HEALTH*	
1		W		W		VB	
2		W		M		B	
3		W		S		B	
4		M		W		B	
5		**M (0.50)**		**M (0.38)**		**A**	**(0.19)**
6		**M (0.50)**		**S (0.63)**		**G**	**(0.31)**
7		S		W		A	
8		**S (0.50)**		**M (0.38)**		**G**	**(0.19)**
9		**S (0.50)**		**S (0.63)**		**VG**	**(0.31)**

KNOW

	If	*R&D exp.*	*AND*	*Employee education exp.*	*AND*	*Employee education hours*	*THEN*	*KNOW*	
1		W		W		W		VB	
2		W		W		M		VB	
3		**W (0.51)**		**W (0.75)**		**S (1)**		**B**	**(0.38)**
4		W		M		W		B	
5		W		M		M		B	
6		**W (0.51)**		**M (0.25)**		**S (1)**		**B**	**(0.12)**
7		W		S		W		B	
8		W		S		M		B	
9		W		S		S		A	
10		M		W		W		B	

11	M	W	M	B	
12	**M (0.49)**	**W (0.75)**	**S (1)**	**B**	**(0.37)**
13	M	M	W	B	
14	M	M	M	A	
15	**M (0.49)**	**M (0.25)**	**S (1)**	**A**	**(0.12)**
16	M	S	W	A	
17	M	S	M	A	
18	M	S	S	A	
19	S	W	W	B	
20	S	W	M	A	
21	S	W	S	A	
22	S	M	W	A	
23	S	M	M	G	
24	S	M	S	G	
25	S	S	W	G	
26	S	S	M	G	
27	S	S	S	VG	

Table 12 Sensitivity analysis spreadsheet

	x_c	-10%	10%	-10%	10%	-10%	10%	-10%	10%
		OSUS (Xc+δ)		Δ_c		D_c		$\lvert D_c \rvert$	
GHG emissions [ton/ton prod]	0.87	0.5650	0.5290	0.018	-0.018	0.0024	-0.0024	0.0024	0.0024
Air emissions [kg/ton prod]	0.97	0.5472	0.5466	0.000	0.000	0.0000	0.0000	0.0000	0.0000
Energy use [GJ/ton prod]	0.82	0.5705	0.5161	0.0236	-0.031	0.0042	-0.0055	0.0042	0.0055
Waste generated [ton/ton prod]	0.95	0.5473	0.5465	0.000	0.000	0.0000	0.0000	0.0000	0.0000
% waste recycled	0.26	0.5415	0.5522	-0.005	0.005	-0.0040	0.0039	0.0040	0.0039
% waste to landfill	**0.11**	0.5541	0.5412	0.007	-0.006	0.0064	-0.0050	**0.0064**	**0.0050**
Water use [ton/ton prod]	1.00	0.5470	0.5465	0.000	0.000	0.0000	0.0000	0.0000	0.0000
COD emissions [ton/ton prod]	0.96	0.5470	0.5467	0.000	0.000	0.0000	0.0000	0.0000	0.0000
Wastewater discharge [ton/ton prod]	0.87	0.5476	0.5461	0.001	-0.001	0.0001	-0.0001	0.0001	0.0001
Community service [hr/emp/yr]	0.94	0.5362	0.5532	-0.011	0.006	-0.0006	0.0003	0.0006	0.0003
Donations [% of sales]	0.75	0.5359	0.5579	-0.011	0.011	-0.0028	0.0027	0.0028	0.0027
Female %	0.32	0.5418	0.5519	-0.005	0.005	-0.0035	0.0034	0.0035	0.0034
Avg emp tenure [yr]	0.61	0.5391	0.5611	-0.008	0.014	-0.0030	0.0055	0.0030	0.0055
Revenue per emp [mil $/emp]	0.66	0.5397	0.5550	-0.007	0.008	-0.0024	0.0027	0.0024	0.0027
ROE (%)	**0.38**	0.5386	0.5551	-0.008	0.008	-0.0051	0.0051	**0.0051**	**0.0051**
Accident Rate[%]	0.96	0.5472	0.5466	0.000	0.000	0.0000	0.0000	0.0000	0.0000
PSM grade	0.85	0.5132	0.5607	-0.034	0.014	-0.0051	0.0021	0.0051	0.0021
R&D exp [% of revenue]	0.30	0.5463	0.5474	-0.001	0.000	-0.0004	0.0004	0.0000	0.0004
Education exp [$/emp]	0.15	0.5460	0.5477	-0.001	0.001	-0.0008	0.0007	0.0008	0.0007
Education time [hr/emp]	1.00	0.5469	0.5469	0.000	0.000	0.0000	0.0000	0.0000	0.0000

Table 13 Basic indicator raw data on Hanwha (2000-2010) [ix] and other selected companies

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	LG [x]	SK [xi]	Dow [xii]	BASF [xiii]	East man [xiv]	Praxair [xv]
Annual prod. [1000MT]	2,911	3,290	3,396	3,395	-	-	-	-	4,278	4,141	4,469	11,650	-	57,000	32,586	7,439	-
GHG emissions [ton/ton prod]	0.54	0.51	0.485	0.48	0.465	0.43	0.37	-	0.41	0.44	0.47	0.49	-	0.67	0.77	0.90	-
Air emissions [kg/ton prod]	-	-	-	-	-	-	-	-	0.012	0.015	0.012	0.168	-	0.400	0.299	4.359	-
Energy use [GJ/ton prod]	-	-	-	-	-	-	-	7.43	7.50	7.84	8.37	8.17	-	9.31	-	11.1	-
Waste generated [ton/ton prod]	8.5	7.45	6.8	7.6	8.5	8.4	8.9	-	8.70	7.13	8.82	8.08	-	24.56	60.46	-	-
% waste recycled	31.2	36.1	40.3	40.8	44.4	-	-	-	39	43	42	70	59	-	48.9	-	-
% waste to landfill	-	-	-	-	54	-	-	-	52	48	53	18	-	22	34.1	-	-
Water use [ton/ton prod]	3.35	2.83	2.54	2.67	2.56	2.51	2.57	2.48	2.61	2.79	2.69	3.78	-	47.25	65.21	-	-
COD emissions [ton/ton prod]	-	-	-	-	-	-	-	-	0.013	0.011	0.008	0.049	-		0.135	-	-
WW discharge [ton/ton prod]	1.139	1.163	1.002	0.998	-	-	-	-	0.90	0.91	0.88	0.100	-	2.5	5.52	-	-
Com. service [hr/emp/yr]	-	-	-	-	-	14.4	16.2		18	17	16	0.70	10.4	-	-	-	-
Donations [% of sales]	-	-	-	-	-	-	-	-	0.13	0.11	0.11	0.06	0.07	0.07	0.10	-	-
Female ratio [%]					4.0	4.1	5.3		7.1	8.7	10.0	9.3	9.4	27	22.5	-	-
Avg emp tenure [yr]	-	-	-	-	-	-	-	-	14.3	14.1	14.1	11.06	15.08	Chemicals industry avg (Korea) = 8.56			
Revenue [mil$]	1,587	1,542	1,395	1,382	1,790	1,884	1,974	2,212	2,703	2,700	3,229	17,330	3,904	53,674	63,873	-	-
Rev. per emp [mil $/emp]	-	-	0.77	0.76	0.98	1.01	1.04	1.14	1.37	1.31	1.49	1.86	0.72	1.07	0.61	-	-
ROE [%]	-1.7	-14.1	2.9	14.3	23.8	21.9	12.1	11.3	1.9	13.6	14.3	25.5%	11.74	10.80	17.8	22.20	25.30

Accident Rate [%]	-	-	-	-	-	0.25	0.21	0.16	0.06	0.13	0.0	0.31	0.23	0.026	-	0.12	-
PSM grade	>90	>90	>90	>90	>90	>90	>90	>90	94	95	97	-	-	-	-	-	-
R&D exp [% of revenue]	-	-	-	-	-	1.0	0.9	-	0.9	1.2	1.1	2.5	2.5	2.8	2.3	4.90 (DuPont)	0.90
Education time [hr/emp]	-	-	-	-	-	-	-	-	0.15	0.06	0.06	0.05	1.3	-	0.32	2.4	-
Education exp [$/emp]	-	-	-	-	-	-	-	-	80	68	85	-	54	32	32.8	-	-

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