CHAPTER IV
RESULTS AND DISCUSSIONS

4.1 Financial and Environmental Impact Assessment

4.1.1 Optimization Variables and Uncertainty Parameters

In summary, the initial set of design variables and uncertainty parameters consist of four variables, and uncertainty parameters (see Table 4.1). In addition, Table 4.1 includes distribution types assumed for the uncertainty parameters and design specification in each design name shown in Table 4.2. In this case, the vinyl chloride monomer production plant plan to set up in Map Ta Phut Industrial Estate, Thailand, and start to operate in year 2007 with a project lifetime of 20 years.

Table 4.1 Definition of optimization variables and uncertainty parameters

Variable description	Variable type	Value of design variables / Distribution type
Capacity	Discrete	300,000 ton of VCM / year 400,000 ton of VCM / year 500,000 ton of VCM / year
Heat Integration	Discrete	No Heat Integration Heat Integration
%HCl Recovery	Discrete	0 %HCl Recovery 50 %HCl Recovery 100 %HCl Recovery
Treatment System	Discrete	No Treatment System Treatment System
All of the release chemicals	Uncertainty	Normal distribution with 10% uncertainty
All of the environmental impact indexes of chemical k in each category	Uncertainty	Normal distribution with 10% uncertainty
Labor cost in each year ($/year)	Uncertainty	Normal distribution with 10% uncertainty
Cost of utility consumption ($/ton of VCM)	Uncertainty	Normal distribution with 10% uncertainty
Purchased Equipment ($)	Uncertainty	Normal distribution with 30% uncertainty
Minimum acceptable annual rate of return, M_{ar}, (percent/100)	Uncertainty	Uniform random distribution between 0.08 and 0.15
Ethylene price ($/ton)	Uncertainty	Normal distribution with S.D.= 107.38
VCM price ($/ton)	Uncertainty	Normal distribution with S.D.= 114.06
Demand of VCM in Thailand (ton/year)	Uncertainty	Normal distribution with S.D.= 14760
Price of HCl ($/ton)	Uncertainty	Normal distribution with mean value = 273 and S.D.= 73.7
Price of Cl_2 ($/ton)	Uncertainty	Normal distribution with mean value = 210.4 and S.D.= 69.7
Price of O_2 ($/ton)	Uncertainty	Normal distribution with mean value = 40 and 10% uncertainty

Table 4.2 Design specification

Design name	Treatment System	Plant Capacity (,000 ton/year)	%HCl recycle[i]	Heat Integration
1	No	300	0	No
2	No	300	50	No
3	No	300	50	Yes
4	No	300	100	No
5	No	300	100	Yes
6	No	400	0	No
7	No	400	50	No
8	No	400	50	Yes
9	No	400	100	No
10	No	400	100	Yes
11	No	500	0	No
12	No	500	50	No
13	No	500	50	Yes
14	No	500	100	No
15	No	500	100	Yes
1T	Yes	300	0	No
2T	Yes	300	50	No
3T	Yes	300	50	Yes
4T	Yes	300	100	No
5T	Yes	300	100	Yes
6T	Yes	400	0	No
7T	Yes	400	50	No
8T	Yes	400	50	Yes
9T	Yes	400	100	No
10T	Yes	400	100	Yes
11T	Yes	500	0	No
12T	Yes	500	50	No
13T	Yes	500	50	Yes
14T	Yes	500	100	No
15T	Yes	500	100	Yes

4.1.2 Expected Net Present Worth and Expected Environmental Impact

The results are summarized in Table 4.3, Figure 4.1, and Appendix D which show method of calculations.

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[i] HCl is assumed as a salable by-product in the designs having %HCl recycle lower than 100%.

Table 4.3 Expected net present worth, environmental impact, and their standard deviations

Design	Economic Aspect		Environmental Aspect		
	E(NPW), $	S.D.	E(EI), EIU/ton of VCM	S.D.	Lj[i]
1	269,403,952	172,914,137	251.41	21.70	0.5755
2	109,795,167	137,928,042	360.29	27.45	1.1304
3	134,126,282	136,215,825	360.29	27.45	1.0492
4	61,926,780	128,240,372	468.89	34.54	1.7216
5	78,794,266	127,063,166	468.89	34.54	1.6589
6	358,095,960	218,341,623	241.41	20.54	0.5095
7	180,317,553	161,175,438	346.34	26.32	1.0747
8	195,925,996	160,183,391	346.34	26.32	1.0222
9	108,190,190	148,554,988	445.28	32.45	1.6303
10	124,824,233	147,484,191	445.28	32.45	1.5703
11	309,574,679	251,422,506	271.65	22.90	0.6652
12	74,165,341	212,885,542	371.48	28.41	1.3317
13	95,085,356	211,285,671	371.48	28.41	1.2612
14	74,787,072	181,432,894	469.16	34.55	1.9397
15	94,640,509	180,070,883	469.16	34.55	1.8662
1T	247,575,641	174,715,036	4.86	0.54	0.0811
2T	87,556,349	140,143,551	5.75	0.62	0.4041
3T	110,765,996	138,471,273	5.75	0.62	0.3254
4T	34,771,876	130,931,931	7.16	0.80	0.7763
5T	52,849,398	129,660,293	7.16	0.80	0.7097
6T	334,532,151	220,223,579	4.91	0.54	0.0400
7T	154,717,747	163,645,844	5.98	0.66	0.3847
8T	169,265,927	162,672,757	5.98	0.66	0.3358
9T	79,014,919	151,329,363	7.12	0.79	0.7393
10T	95,817,739	150,218,763	7.12	0.79	0.6789
11T	282,454,066	254,000,534	4.90	0.55	0.1369
12T	43,296,484	216,102,884	5.97	0.67	0.5982
13T	64,399,179	214,474,673	5.97	0.67	0.5271
14T	41,423,542	184,807,948	7.17	0.80	1.0050
15T	62,887,093	183,338,879	7.17	0.80	0.9261

Figure 4.1 is plotted between expected net present worth, environmental impact, and their standard deviations in each design found that standard deviation values not only directly relate to the uncertainty parameters in each design, but also depend on the number of the uncertainty parameters. The

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[i] Consider only two-objective: maximizing E(NPW) and minimizing E(IE)

combination of several uncertainty parameters can increase the standard deviation range. This work considers several uncertainty parameters (see Table 4.1) which are some parameters with high uncertainty, so the standard deviations are really large.

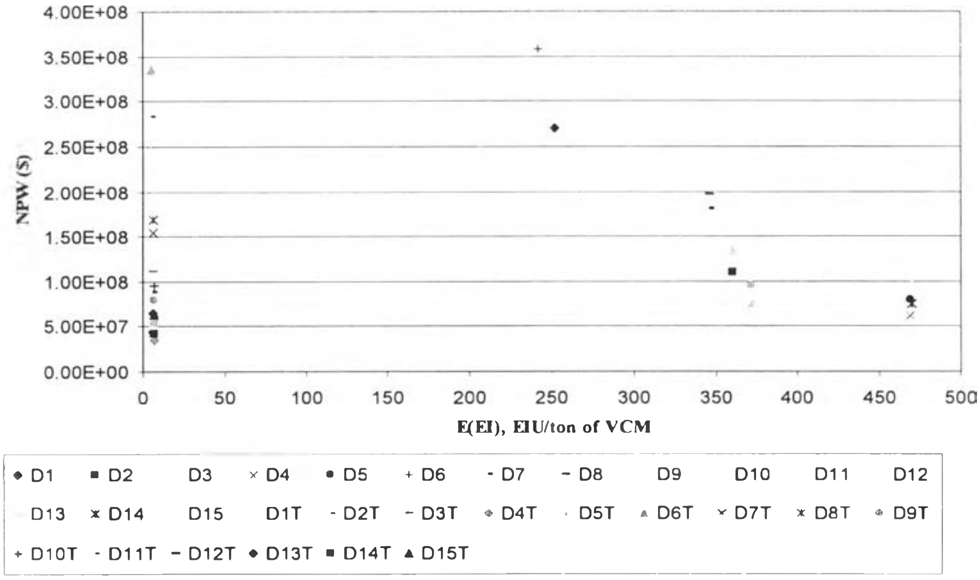

Figure 4.1 Relationship between expected net present worth, E(NPW), environmental impact, E(EI) in each design.

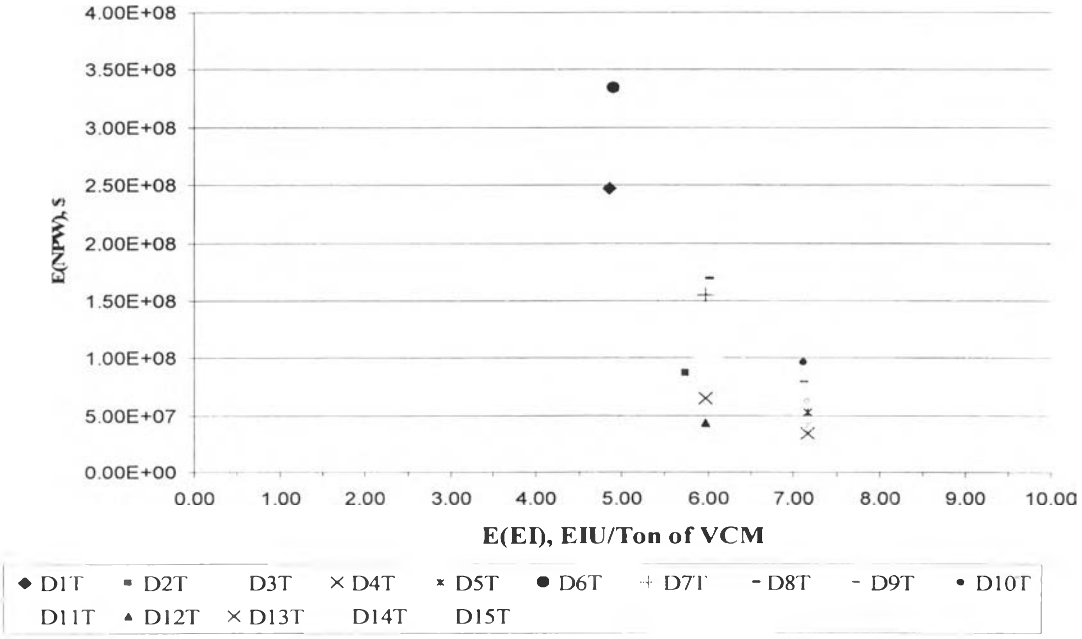

Figure 4.2 Relationship between expected net present worth, E(NPW), environmental impact, E(EI) in the designs with treatment system.

From Figures 4.1 and 4.2, if only two objectives under uncertainty condition, which are maximizing E(NPW), and minimizing E(EI), is selecting criteria and giving that equal weights to each objective were assigned (see Table 4.3), the optimum solution is Design 6T, which obtains the lowest L_j, operating with the treatment system at a plant capacity of 400,000 tons of VCM/year, no heat integration, and no HCl recycle, giving an expected NPW of \$334,532,151 ± 220,223,579 and an environmental impact of 4.91 ± 0.54 EIU/ton of VCM.

The results can be classified into three groups (Figure 4.1, 4.2 and Table 4.3) which the designs without HCl recycle obtain higher E(NPW) and lower E(EI) than HCl recycle. The reason of the results is low selectivity of ethylene to VCM in the oxy-chlorination process and quite large amount of by-products which are sources of environmental problem. Additional, energy consumption in oxy-chlorination is required more that in the direct chlorination process. The design in each group is found that the designs operate at a plant capacity of 400,000 tons of VCM/year obtaining higher E(NPW) than the other designs because the demands of VCM from year 2007-2026 are in the range of 260-1039 tons/year (see Appendix C) that a plant capacity of 400,000 tons of VCM/year has more suitable capacity than the other capacities. The capacity of 300,000 tons/year is quite low which compare with its demand. The capacity of 500,000 tons/year is quite high and difficult to reach production capacity of 500,000 tons/year until year 2013.

Although, this methodology takes into account the uncertainties present when evaluating process alternatives, the method cannot explain how much risk it is that we are taking, which can be dangerously misleading.

4.2 Financial and Environmental Risks

4.2.1 Financial Risks

Figures 4.3 and 4.4 show NPW cumulative probability curves of each design or financial risk curves.

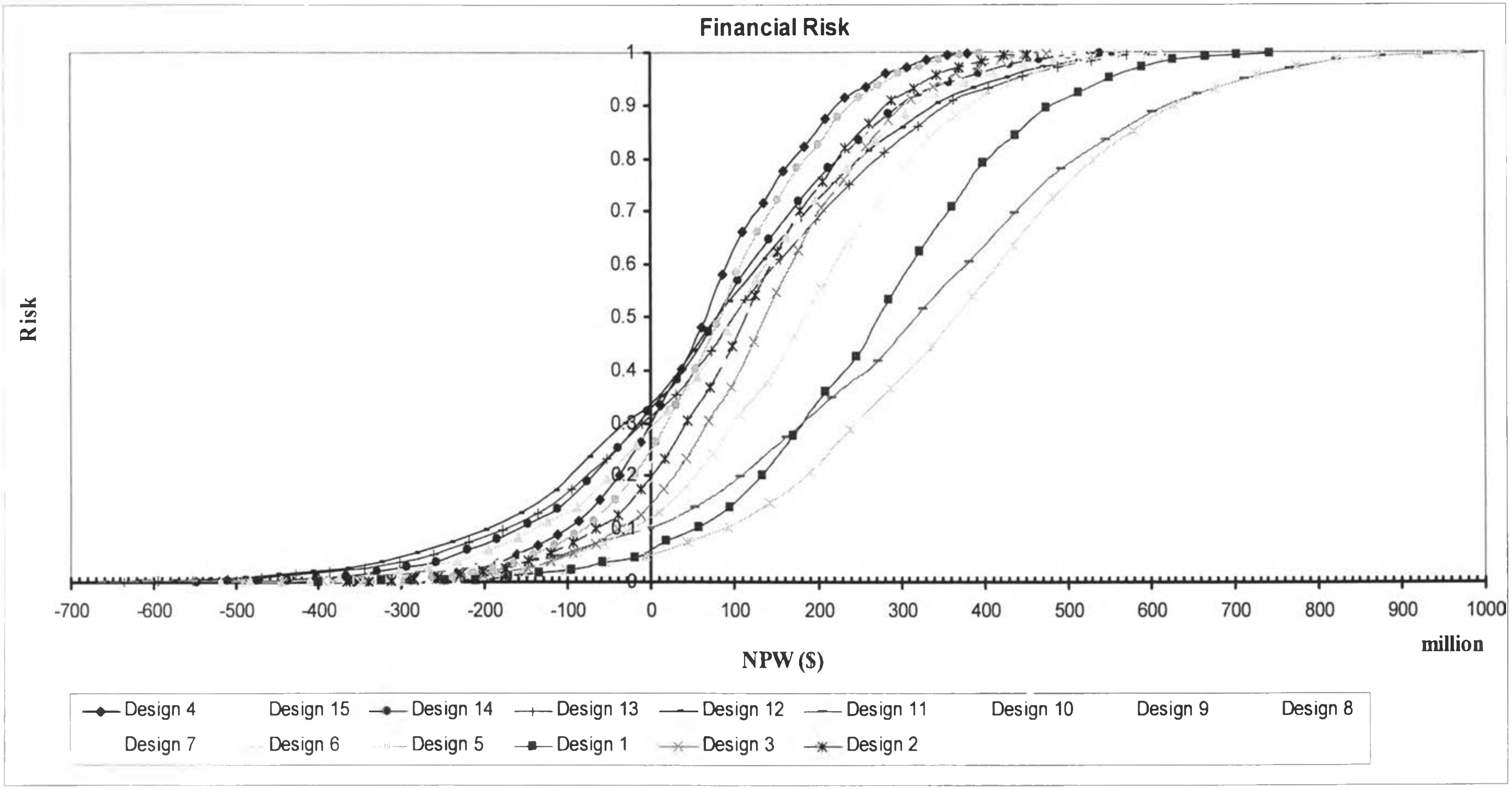

Figure 4.3 Financial risk curves without the treatment system.

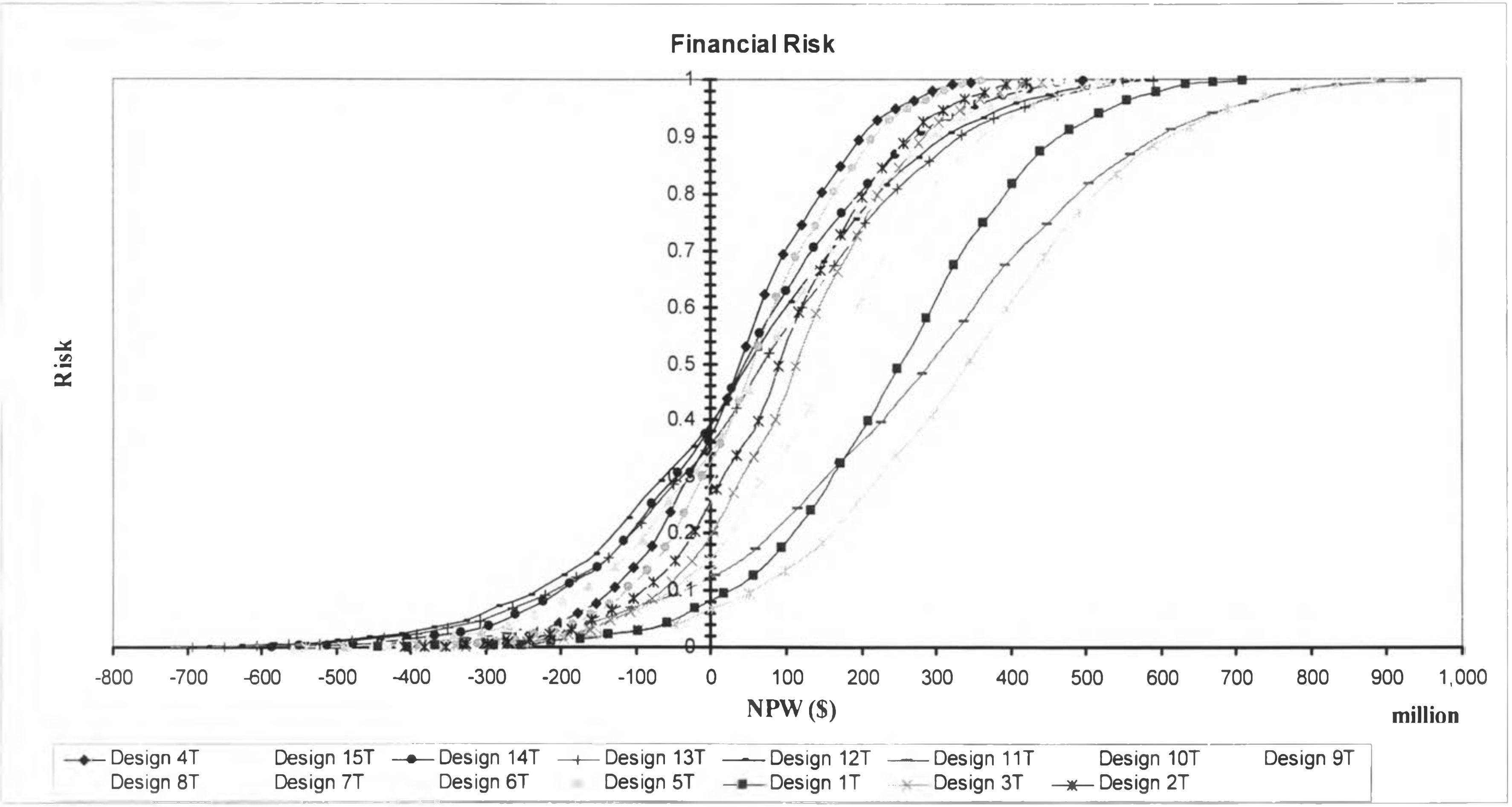

Figure 4.4 Financial risk curves with the treatment system.

Comparison among the designs with the treatment system in Figure 4.4 and without the treatment system in Figure 4.3, it can be found that financial risk curves have similar shapes, but the probabilities of losing money increase because of augmentation of cost in the treatment units.

However, the treatment system can decrease environmental impact, dramatically, and can be used in the real system due to forcing of the regulations. So, financial risk analysis shows the Design 6T is the best solution in the real system because it obtains the highest expected NPW of \$334,532,151 ± 220,223,579 and lowest risk of losing money which is 6.5%.

Figures 4.5-4.8 illustrate the comparison among design variables which have effects on financial risk. From Figure 4.5, the best plant capacity among the three designs is 400,000 tons/year, obtaining the lowest risk for all of the target NPWs, is a suitable capacity for the demand of VCM in Thailand. Increasing %HCl recycle rises risk, so the best %HCl recycle is 0%HCl recycle (see Figure 4.6). From Figures 4.7 and 4.8, the designs without treatment system and with heat integration give lower risk.

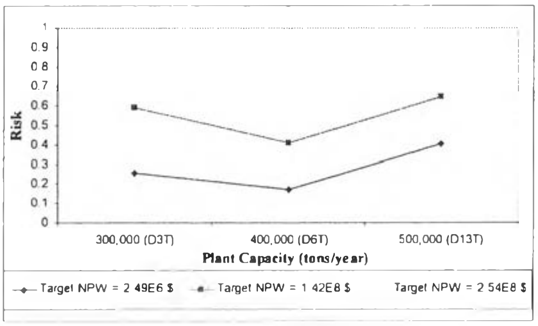

Figure 4.5 Relationship between plant capacities and financial risk.

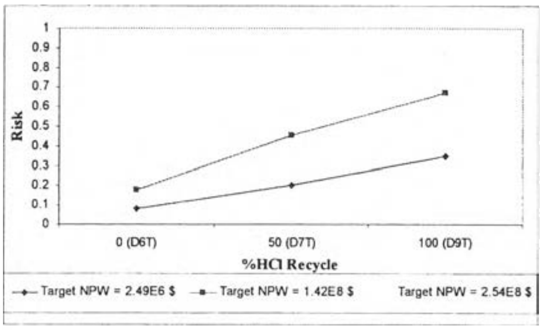

Figure 4.6 Relationship between %HCl recycles and financial risk.

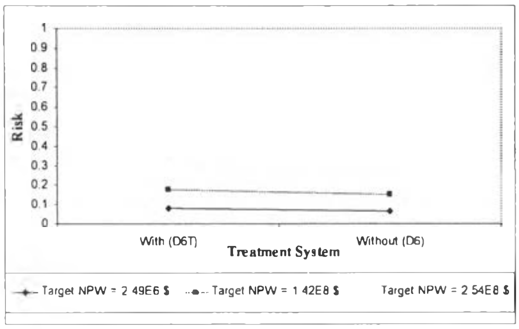

Figure 4.7 Relationship between with and without treatment systems and financial risk.

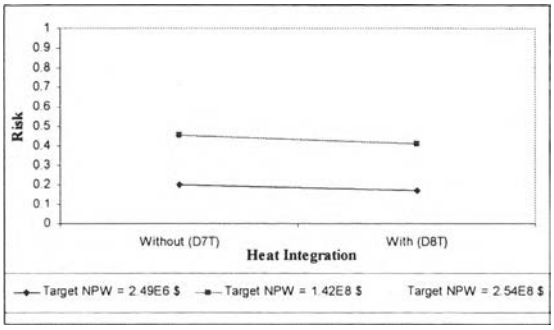

Figure 4.8 Relationship between with and without heat integrations and financial risk.

4.2.2 Environmental Risks

For the case study discussed in this work, the predominant emissions from a VCM plant were used (CO_2, SO_2, C_2H_4, Cl_2, EDC, VCM, TCE, and HCl) to perform potential environmental impact and the method of calculation is shown in Appendix E

Designs without the treatment system shown in Figure 4.5 and with treatment system shown in Figure 4.6 suggest that all of the environmental risk curves have similar shapes, in addition, they can be classified into three groups in Figure 4.5 and Figure 4.6 because the difference of design specification in %HCl recycle, that is, the higher HCl recycle the higher environmental impact. The reason of the results is low selectivity of ethylene to VCM in the oxy-chlorination process and quite large amount of by-products which are sources of environmental problem. Additional, energy consumption in oxy-chlorination is required more that in the direct chlorination process.

Comparison between designs with the treatment system and without the treatment system, it is found that the environmental impact of the designs without the treatment system is far higher than the designs with the treatment system. The predominant emission chemicals in the designs without the treatment system are CO_2, and SO_2, mainly from furnaces, and ethylene, chlorine, EDC, VCM, TCE, and HCl, which are by-products, raw materials and products of the VCM production process. On the other hand, the design with the treatment system releases only CO_2

and SO_2 which is mainly from furnace units and incineration system which is used to eliminate the emissions of by-products, raw materials, and products of the VCM production process.

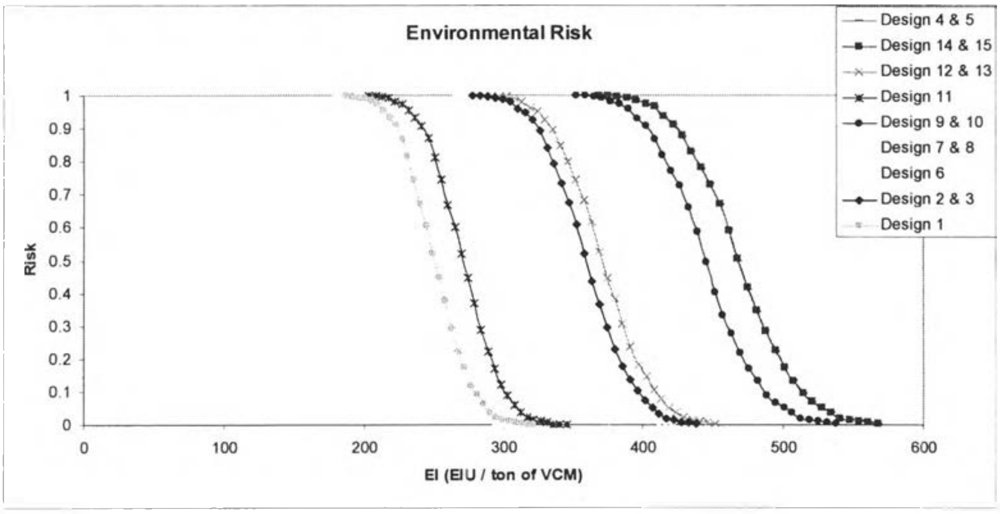

Figure 4.9 Environmental risk curves without the treatment system.

For expected environmental impact, Figure 4.9 shows that the best solution, which have the lowest E(EI) and the lowest risk, is Design 6, but the environmental law in Thailand regulates the emission of dangerous chemicals such as EDC, VCM, TCE and HCl lower than the values obtained from this design, so this design cannot be set up.

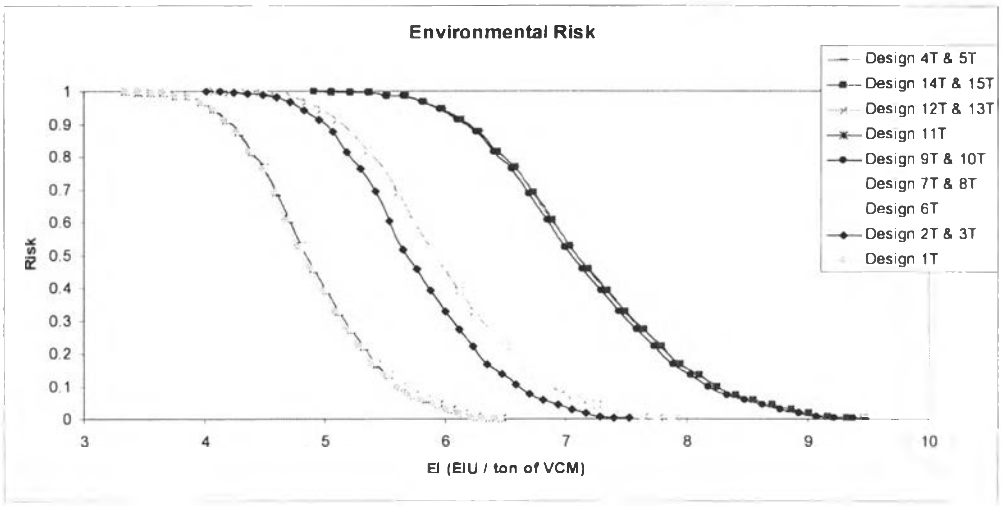

Figure 4.10 Environmental risk curves with the treatment system.

Figure 4.10 reveals that Design 1T is the best solution having the lowest E(IE) and the lowest risk.

Figures 4.11-4.12 show the comparison among design variables which have effects on environmental risks. The design with 0%HCl recycle and a plant capacity of 400,000 tons/year is better than the others.

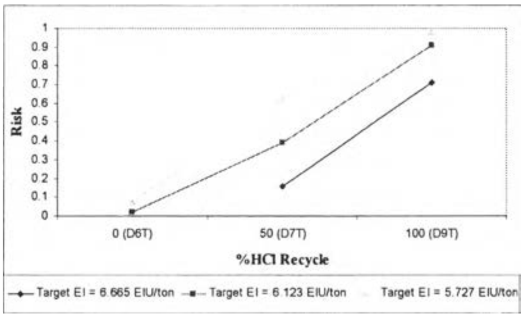

Figure 4.11 Comparison among %HCl recycles.

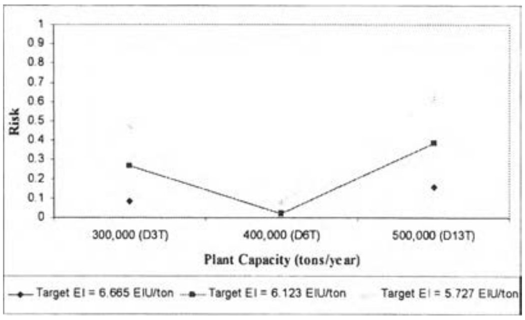

Figure 4.12 Comparison among plant capacities.

4.3 Multiobjective Optimization

Equal weights to each objective were assigned for both financial risk and environmental risk. Then, the best design at each risk can be found by using multiobjective optimization method. The final solution is chosen by a decision-maker based on his preferences; i.e., a risk-averse decision-maker may want to have low risk for some conservative low aspiration level, whereas a risk-taker would prefer to see lower risk at higher aspiration level, even if the risk at lower target value increases.

Table 4.4 Optimization results for the VCM plant

Risk (i)	Min $L_{j,i}$ / Design	Design 6T at Risk i		$NPW_{max,i}$ ($)	$NPW_{min,i}$ ($)	$EI_{max,i}$	$EI_{min,i}$
		NPW_i ($)	EI_i (EIU/ton of VCM)			EIU/ton of VCM	
0.25	0.15 / 6T	190,654,000	5.271	215,417,000	-102,520,000	492	5.23
0.50	0.13 / 6T	342,875,000	4.845	363,407,000	38,706,300	468	4.86
0.75	0.12/ 6T	477,576,000	4.536	498,163,000	122,726,000	446	4.50

Table 4.4 shows the best compromise solutions at each risk and Design 6T is the best compromise solution at each risk point[i] because it possesses the lowest $L_{j,i}$. Besides, the higher risk gives the higher target levels (higher NPW, lower IE).

From Table 4.4, if a decision maker can accept the risk of 0.25, the best design is D6T which have a chance of getting NPW lower than $190,654,000 and EI higher than 5.271 equal to 0.25.

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[i] In usual, the best design at a risk may not be the best design at another risk.