CHAPTER IV
RESULTS AND DISCUSSION

4.1 Process Description

Catalytic reforming is a process for improving the octane quality of straight-run naphtha. The main reaction is dehydrogenation of naphthenes to aromatics, which are high in octane value. Contributing to the high octane of the product, there also are side-reactions such as hydrocracking of high-boiling hydrocarbons to low molecular weight paraffins, isomerization of paraffins to branched-chained structure and dehydrocyclization of paraffins and olefins to aromatics. Normally, a typical reforming catalyst contains platinum and chloride on alumina base. Figure 4.1 show the typical process flow sheet of catalytic reforming. In addition, there is the table describing the input and output chemicals in the process in Table 4.1.

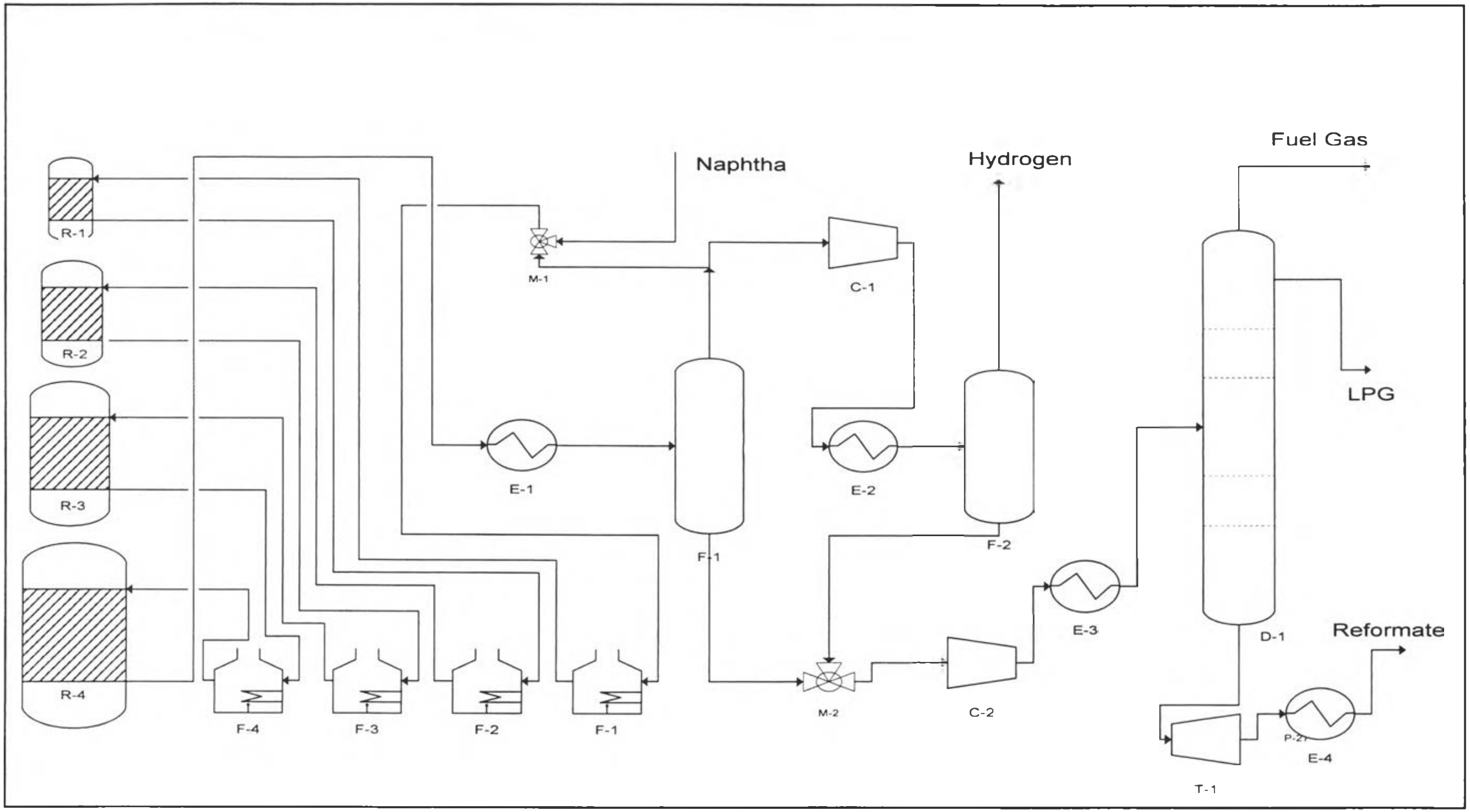

Figure 4.1 Catalytic reforming process flow sheet.

Table 4.1 Input and output chemicals in process

Chemical Type	Chemical Substances
Raw material	Naphtha
Product	Reformate
By-products	Hydrogen, LPG

4.2 Data Assessment

4.2.1 Financial Data Assessment

4.2.1.1 Equipment Cost

The equipment costs of each basis design (plant capacity = 20 kbd) were appeared in Table 4.2.

Table 4.2 Equipment costs of basis design (plant capacity = 20 kbd)

Reactor temperature	Heat exchanger network type	Cost (MM$) (in year 2009)
495°C	pinch practical	52.334 52.251
501 °C	pinch practical	54.445 54.300

Accordingly, those costs were used to substitute in Equation 4.1 to represent exponential model for finding equipment costs of other capacities.

$$\frac{C_1}{C_2} = \left(\frac{PC_1}{PC_2}\right)^{0.6} \tag{4.1}$$

where C = equipment cost, PC = plant capacity, 1 = basis case (capacity = 20 kbd), 2 = others cases.

4.2.1.2 Raw material, Fuel oil Usage and By-product Production

From kinetic reaction, mandatory raw materials and formed by-product amounts were revealed. Nevertheless, two different reformate types, containing 73% and 77% aromatic, are obtained according to the increased temperatures, 495°C to 501°C. Furthermore, fuel oil usage was received from doing heat integration. Those were shown in Tables 4.3 and 4.4.

In those tables, data were informed in ratio of each type value to reformate production rate, for convenience in calculation.

Table 4.3 Raw material usage and by-product production

Types of chemical substances in process	Temperature at Reactor	
	495°C	501°C
Naphtha / Reformate, [%vol]	117.53	119.54
Hydrogen / Reformate, [(scm) / kbl]	56115.25	60402.69
LPG / Reformate, [kg/kbl]	504.857	606.172

Practically, the reactor temperature is indicator of severity. The higher severity means lower reformate yield but higher quality of reformate-lower octane number. Besides, the cracked hydrocarbon molecule amount is increased when it is operated at high severity. Thus, the above data confirms that fact of thermodynamics of this process. For the below table, the lower operating temperature and pinch heat integration lead to the lower utility usage, corresponding to theory.

Table 4.4 Fuel usage

Type of Fuel	Heat exchanger network			
	Pinch type		Practical type	
	Reacting Temperature			
	495°C	501°C	495°C	501°C
Fuel oil / Reformate [%vol]	22.25	22.82	23.12	23.69
Water / Reformate [m^3/kbl]	205.58	213.57	205.58	213.57

4.2.2 Environmental Data Assessment

Basically, amounts of benzene and carbon dioxide attribute to an environmental hazard. So, in this work, quantities of both things, occurred due to production, were calculated to evaluate environmental impact.

4.2.2.1 Benzene

Amount of benzene produced could be calculated by means of kinetic reaction model. The results of different operating temperatures are shown in Table 4.5. From this table, it illustrate the fact that the higher temperature, the more benzene production.

Table 4.5 Benzene occurrence

Hazard Substance	Reacting Temperature	
	495°C	501°C
Benzene mass / Reformate volume [(kg/hr) / kbd]	137.40	140.62

4.2.2.2 Carbon dioxide

Different heat exchanger types, including different operating temperatures cause various particular carbon dioxide released amounts. Those values were declared in Table 4.6. Besides, the flow sheets of both heat exchanger network types are exhibited in Appendix B.

Table 4.6 Carbon dioxide occurrence

Hazard Substance	Heat exchanger network			
	Pinch type		Practical type	
	Reacting Temperature			
	495°C	501°C	495°C	501°C
Carbondioxide / Reformate [(kg/hr) / kbd]	454.12	459.86	463.37	477.40

4.3 Financial and Environmental Impact Evaluations

4.3.1 Expected Profits and Environmental Impacts

The result was summarized in Table 4.7 and Figure 4.2. (The calculated method was demonstrated in Appendix C)

Table 4.7 Expected profits and environmental impacts

Plant Capacity	Type of design	Profit ($)	Environmental impact (kg/hr)
14	a	3.72E+07	11,343
	b	4.02E+07	11,550
	c	3.44E+07	11,483
	d	3.60E+07	11,763
20	a	3.77E+07	14,223
	b	4.05E+07	14,481
	c	3.44E+07	14,398
	d	3.55E+07	14,748
26	a	2.20E+07	15,994
	b	2.43E+07	16,284
	c	1.84E+07	16,190
	d	1.89E+07	16,584

where design types are classified in Table 4.8.

Table 4.8 Type of design classification

Type of design	Heat exchanger Network	Reacting Temperature, (°C)
a	Pinch	495
b	Pinch	501
c	Practical	495
d	Practical	501

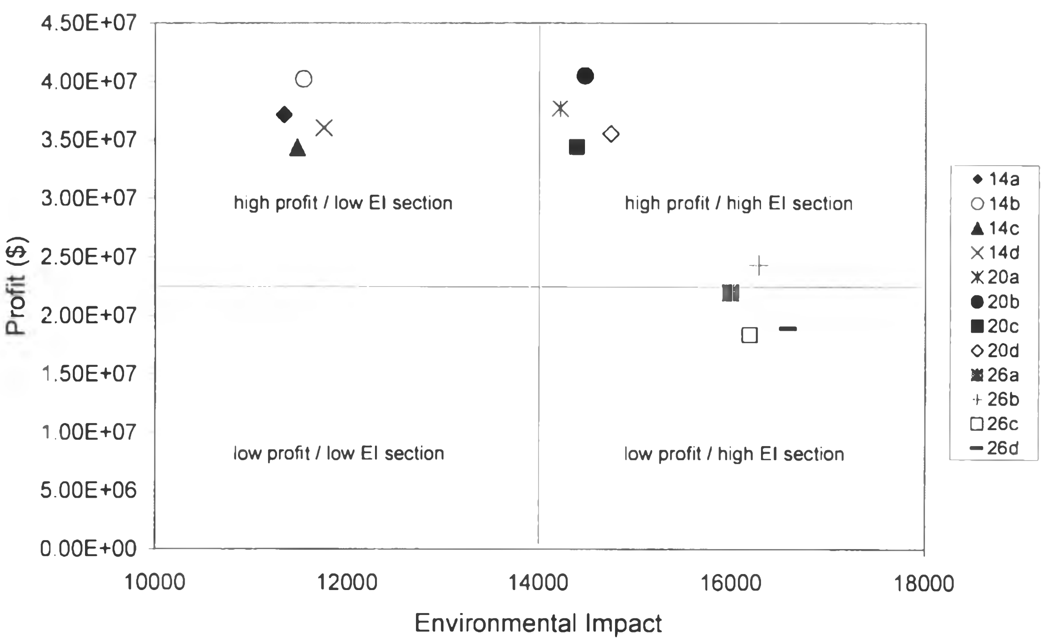

Figure 4.2 Comparison between profits and environmental impacts among each design.

Figure 4.2 is a plot between calculated profit & environmental impact, shown in deterministic value- without uncertainty. The diagram can be classified into four quadrants; i.e. high profit/low environmental impact, high profit/high environmental impact, low profit/high environmental impact and low profit/low environmental impact.

Generally, the decision maker, investor, would favor the design with high profit/low environmental impact. Hence, from Figure 4.2, 14 kbd design seems to be the most desirable design compared to 20 and 26 kbd design respectively.

However, this cannot tell how much risk and uncertainty associated with the design 14 kbd compared to the others. Therefore, the probability curves should be constructed to study the financial and environmental risk of each design, in the next section.

4.3.2 Profit and Environmental Impact Distributions

In this part, the probability curves were constructed by integrating uncertainty parameters (see Appendix E) into the calculation. Then, by the definition of financial and environmental risks (Equation 2.10 and 2.13), the risk curves were created. Those graphs were displayed in Figure 4.3 to Figure 4.6.

Beyond the uncertainty parameter, the shape of curve also depends on the design parameter of each design. Table 3.1 exhibited the impacts of design parameters to the profit and environmental assessment.

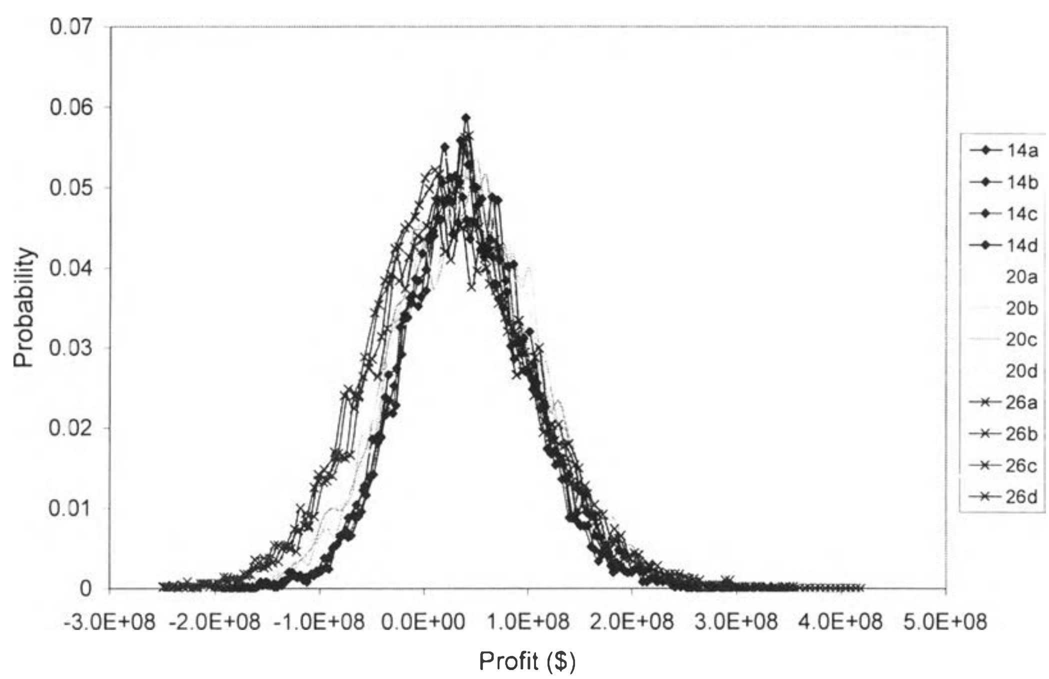

Figure 4.3 Profit probability curves of each design.

From above table, it seems that 26 designs have the broader distribution than the other designs. Thus, that means it has the more opportunity for both reaching the high profit levels and ending with high money loss levels, for the plant with high capacity, production rate.

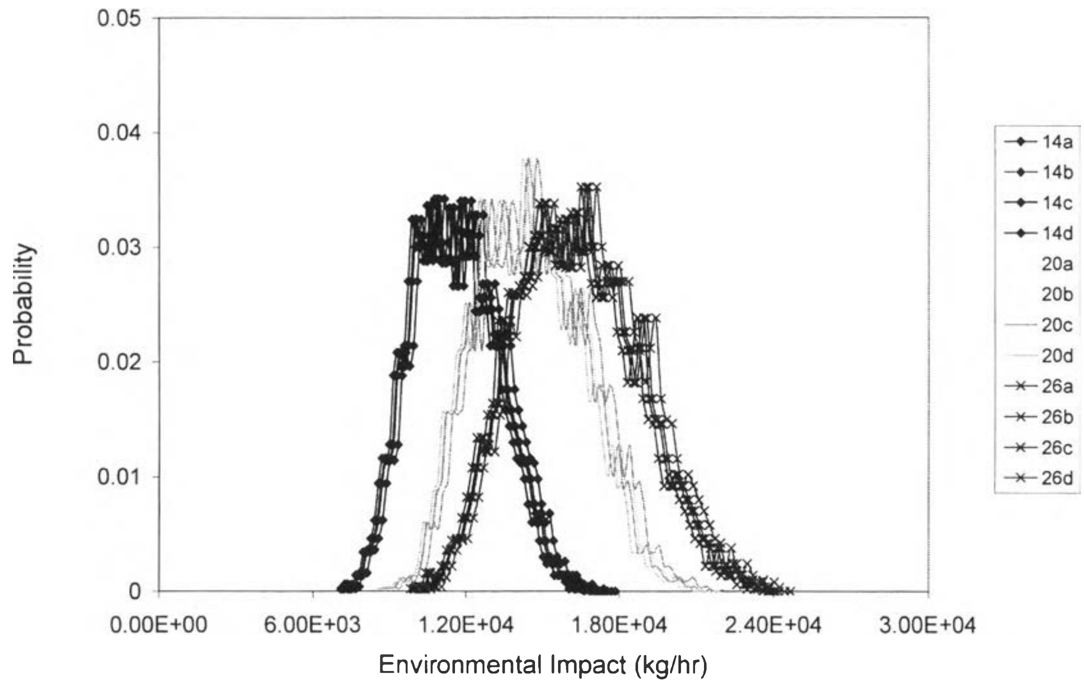

Figure 4.4 Environmental impact probability curves of each design.

In this Figure 4.4, it illustrates that the 14 designs have many chances for generating low environmental impacts, but a few opportunities for producing high impacts when comparing with the others. This is because the lowest production rate leads to smallest harmful substance production.

However, for more straightforward statistic graph, the financial and environmental risk curves are constructed to investigate each design in below figures.

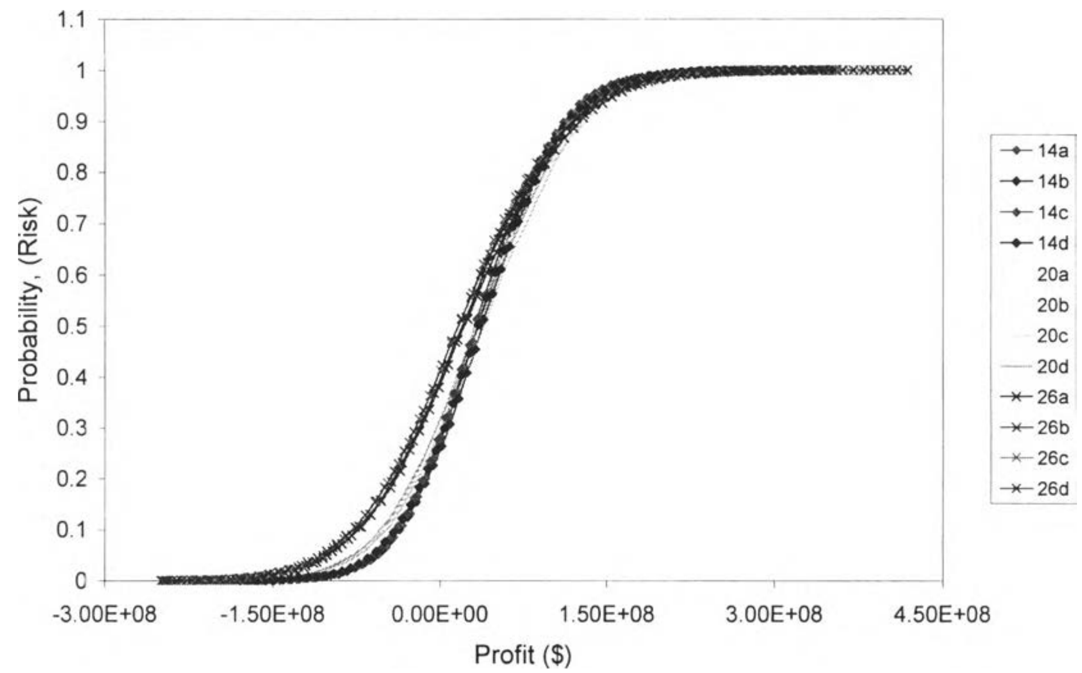

Figure 4.5 Profit cumulative probability curves of each design (Profit risk curves).

From the above figure, it shows the variety of the financial risk characteristic of each design. Normally, the financial risk graph is used as a tool in process evaluation and comparison. However, the financial risk depends on the aspiration target profit of investor. If the investor, for example, wants the design that has the minimum risk at minimum level of not losing money, target profit = 0, the 14b is the most interesting design, having 0.25 risk, whereas the 20c design is the most risky design, having 0.41 risk.

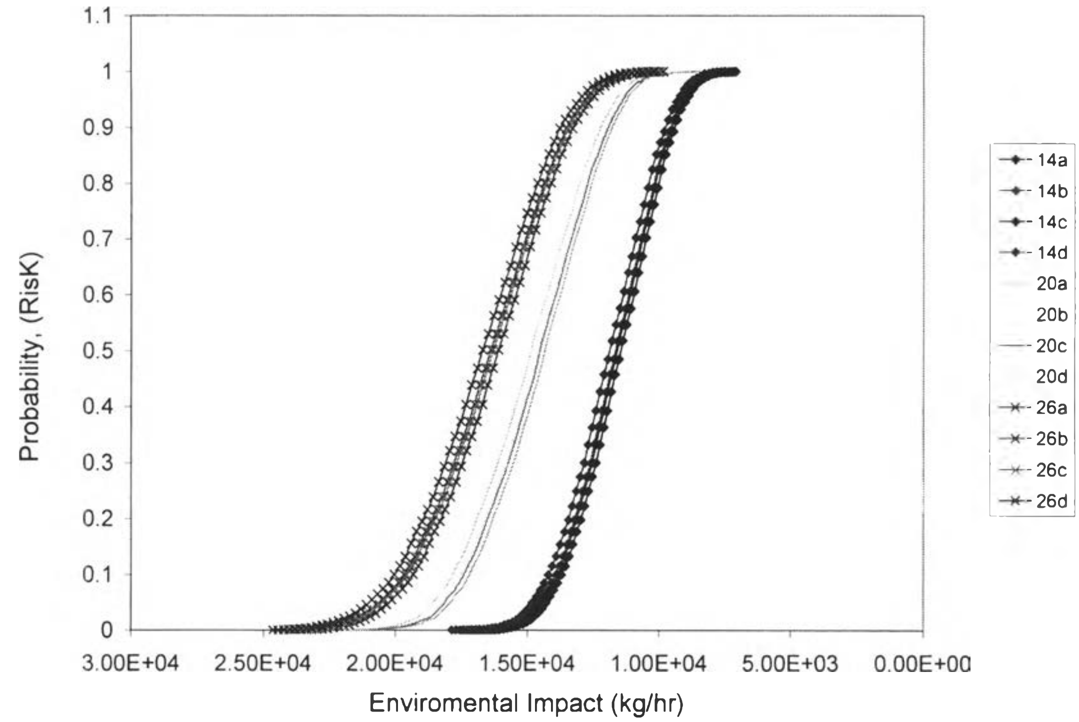

Figure 4.6 Environmental impact cumulative probability curves of each design (Environmental impact risk curves)

For the Figure 4.6, it shows that the idea of the environmental risk graph looks like of the profit risk graph. Risk depends on the target value of each objective.

From Figures 4.3 and 4.5, all of the financial distribution curves of each design have quite similar shape as one another. However for the environmental impact in Figures 4.4 & 4.6, it is likely to have three groups of distribution curves. This is because the environmental impact largely depends on the capacity of plant.

By the way, as one expect, the financial risk curve is always increasing. This reveals that the risk of not achieving relatively small profits is practically small, while at the higher profit levels, the larger risks are normally displayed. Vice versa for the environmental impact risk curve, the risk of over desirable small impact is basically large, whereas the little risks are observed at the higher impact level.

As stated before, the risk relies on the aspiration target of the investor.

Therefore, in the next two graphs below, the three profit levels ($-1.15E+07, 3.55E+07, 8.25E+07) and three environmental impact levels (1.30E+04, 1.46E+04, 1.61E+04 kg/hr) were used to represent the high, medium and low aspiration target levels to show the overviews of risk manners based on the risk curves in Figures 4.5 and 4.6.

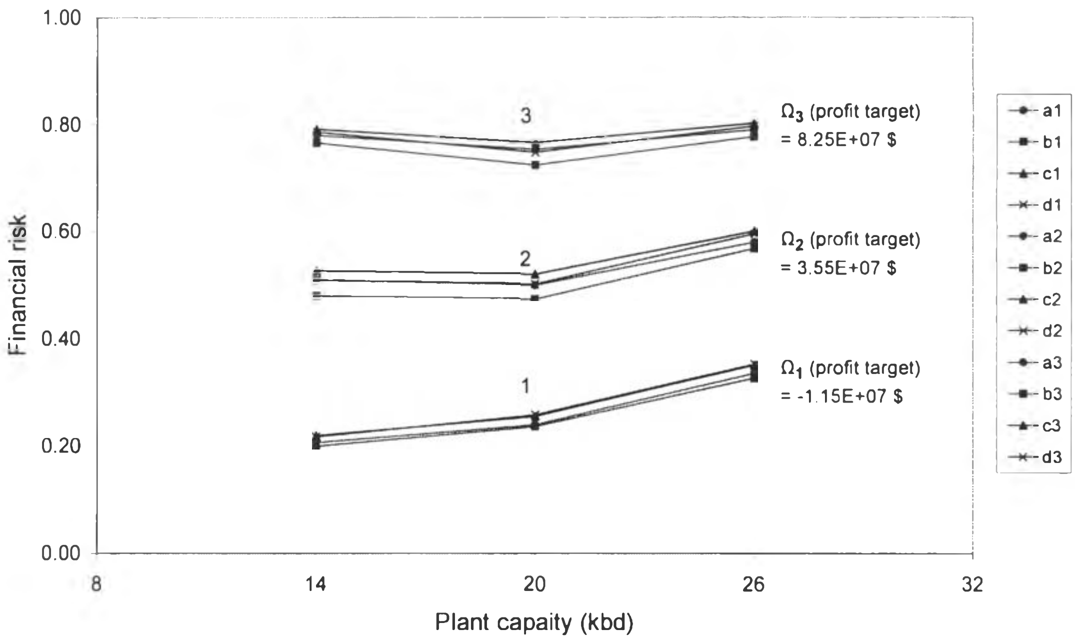

Figure 4.7 Financial risk trend at different profit targets.

From Figure 4.7, it shows that the c design has the highest financial risk, whereas the design b has the lowest financial risk at every profit level. In addition, at the low profit target, $-1.15E+07 (note that this is the financial loss case), the financial risk is increasing according the plant capacity. Whiles, at the medium and high aspiration levels, $3.55E+07 and $8.25E+07, it is likely that 20 kbd design become the least risky design, having lowest financial risk.

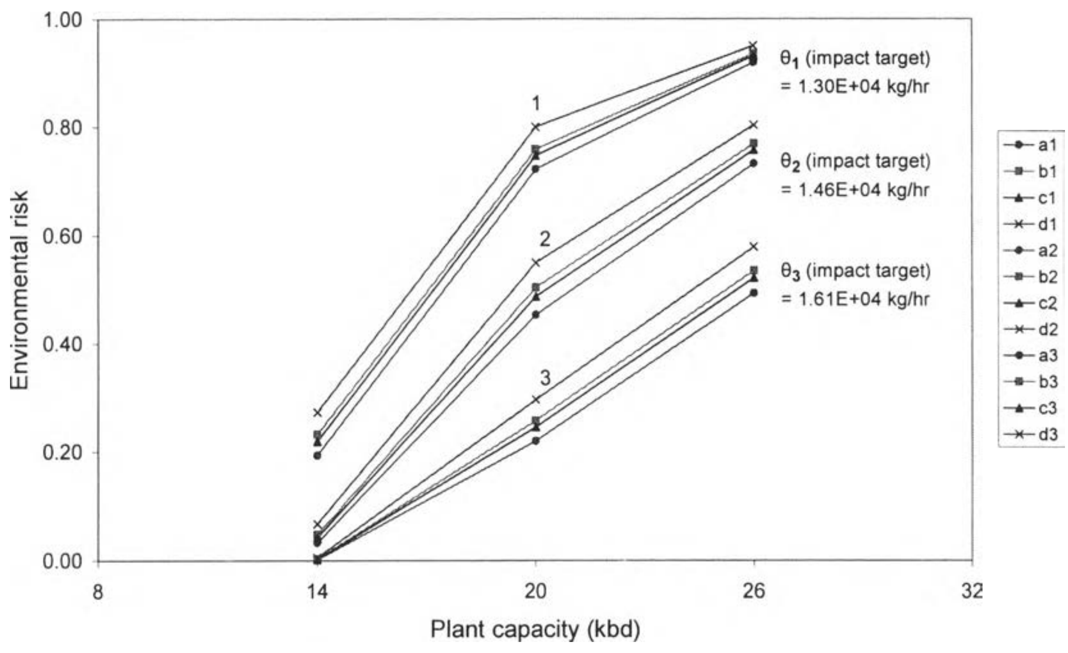

Figure 4.8 Environmental risk trend at different environmental impact targets.

In case of the environmental counterpart, Figure 4.8 reveals the fact that the a design is responsible for the safest design due to the lowest environmental risk at every target level, and in the contrary for the d design. In addition, it is promising that the greater plant capacity, it means the higher environmental risk.

For the expected value, Table 4.7 and Figure 4.2 reveal that both 14 and 20 kbd capacity plants can make more satisfactory profits when comparing with 26 kbd capacity plant. Moreover, they produce less amount of environmental hazard than 26 kbd capacity plant. Therefore, it suggests that it is not good to build a plant at 26 kbd in year 2009.

Typically, regarding the optimum design, because of no definite index comparison between finance and environment, the final decision should be left to the decision maker, who might select the best option based on his preference by giving the weights to each expected value of objectives.

Currently, there is no environmental law about carbon dioxide emission in Thailand. Besides from the kinetic data, the happened amount of benzene does not exceed the gasoline quality regulation, benzene less than 3.5 % volume.

That means all designs in this work can pass the minimum environmental criteria, law regulation. Thus, the profits of each design seem to play an important role in the design selecting step. After considering the financial aspect, the 14b and 20b rather have the better expected profits than any other design.

Hence, the probability curve, shown in Figure 4.9 and 4.10, comes to play the important role in considering the proper process design, especially the risk curve.

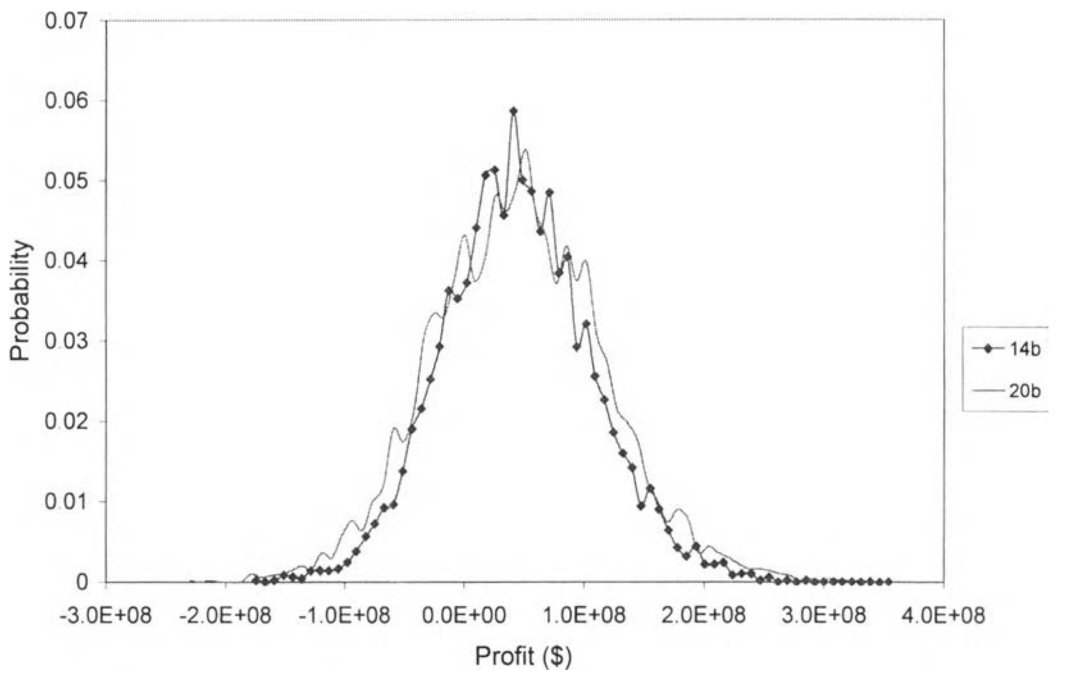

Figure 4.9 Profit probability curves of 14b and 20b designs.

From Figure 4.9, it looks like 14b design has the narrower distribution than 20b design. That means 20b design has the grater chance for both achieving the high profit levels and losing a large number of money. The simpler and more definite curve can be illustrated by the risk curve in Figure 4.10.

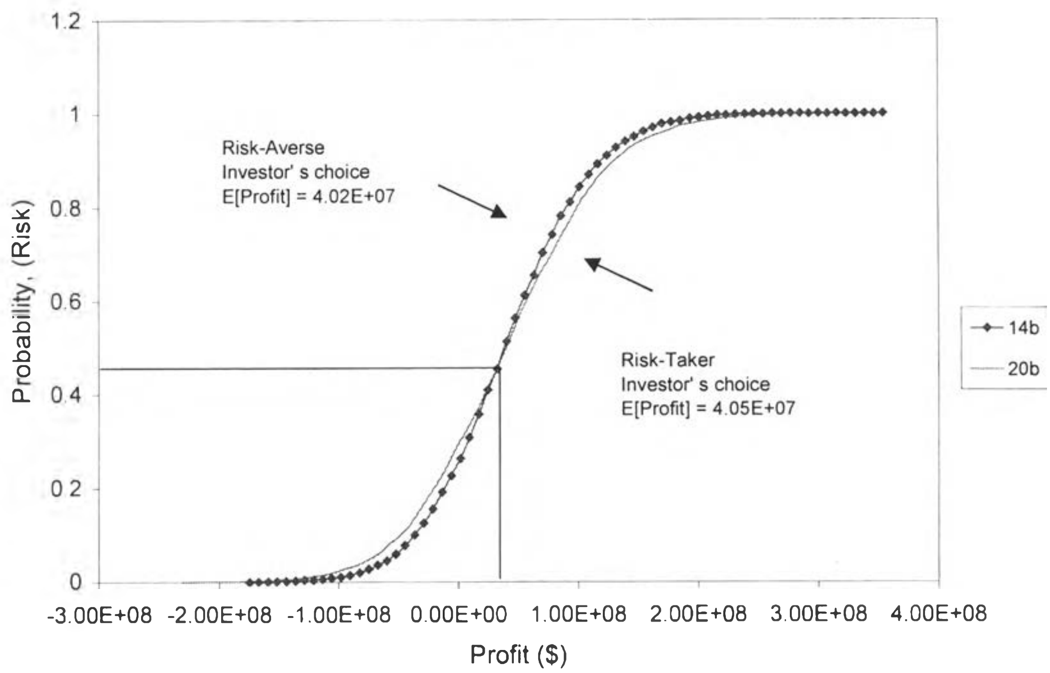

Figure 4.10 Profit cumulative probability curves of 14b and 20b designs (Profit risk curve).

Ordinarily, there are two types of decision makers. A risk-averse investor rather wants to have only low risk for some conservative profit aspiration level. While a risk-taker decision maker would prefer to obtain lower risk at higher profit aspiration level, even the risk at lower profit values increases.

The previous concept can also be applied to the design selection between 14b and 20b, in Figures 4.9 & 4.10, depending on who the decision-maker is, between the risk-averse and risk-taker investors. In another word, if one have a desired target profit at low profit, the 14b design is likely to be the more interesting design for investment because of the lower risk there. Otherwise, if the high profit target is set by the investor, the 20b design is the more preferable one, with the same reason. The critical aspiration profit level, which is used to be basis in design selection, is at the cross point between those two designs. However, if the investor want the design that has only a few risk at 0 $ profit, not losing in business, the 14b design seems to be the best one to select.

4.3.3 Design Optimization

Regardless of the Thai environmental law used as one constraint in a design consideration in the previous step, the multi-objective optimization is applied into this stage to find the most qualified design for both financial and environmental aspects. The summation of weighted objective functions method is used as a tool to find the optimum design. In fact, the resolution should depend on decision maker's particular preferences to finance and environment. To illustrate a one of evaluated method, the equal weights, 0.5, were given to each objective. The values of sum weighted objective were given in Table 4.9. Since the risk is naturally embedded in both two objectives, the values in the below table are calculated at particular risk levels (0.25, 0.50, 0.75) to demonstrate the trends of objective values at the different risk levels.

Table 4.9 Sum weight objective values of each design

Plant Capacity	Type of design	Sum weighted objective		
		Risk = .25	Risk = .50	Risk = .75
14	a	0.46	0.38	0.21
	b	0.48	0.44	0.28
	c	0.41	0.31	0.13
	d	0.40	0.34	0.15
20	a	0.09	0.13	0.06
	b	0.08	0.20	0.20
	c	0.03	0.04	-0.03
	d	-0.01	0.07	0.05
26	a	-0.39	-0.36	-0.36
	b	-0.39	-0.35	-0.28
	c	-0.46	-0.46	-0.46
	d	-0.50	-0.50	-0.45

The above table has shown that if the weight factors are assigned to have an equal number for both financial and environmental objectives, it is most likely that the 14b is the optimum design at every risk level. However, typically the design selection must be based on the decision of investors, which depends on how much awareness they pay on each parameter – finance and environment. The decision method in this work is proposed as a one of options to choose the optimum design for catalytic reforming unit operating in Thailand in year, 2009-2018.