Stochastic capital budgeting approach to obtain the target probability of buckling failure of a wind turbine tower subjected to typhoons in the Philippines

Lessandro Estelito Garciano* and Takeshi Koike**

* M. of Eng., Graduate Student, Dept. of Civil Eng., Musashi Institute of Technology, Tamazutsumi, Setagaya-ku, Tokyo 158-8557
** Dr. of Eng., Professor, Dept. of Civil Eng., Musashi Institute of Technology, Tamazutsumi, Setagaya-ku, Tokyo 158-8557

Buckling failure of wind turbines in typhoon prone-areas is an important issue that needs to be addressed by both designers and wind farm owners. In this paper the authors propose a technical – financial approach to obtain an acceptable target probability of buckling failure that satisfies a financial criterion acceptable to the owner. To obtain the probability of buckling failure reliability analysis is used. On the other hand the cash flow of the wind farm is analyzed using stochastic capital budgeting. The criteria used to assess the cash flow values are the net present value and the internal rate of return methods.

Key Words: Buckling, target probability of failure, typhoons, stochastic capital budgeting, net present value, internal rate of return

1. Introduction

The Philippines is slowly integrating wind energy into its energy mix because of its good potential for wind power development[1]. Unfortunately some of the ideal sites for wind farms in the country are also prone to strong typhoons. Due to this phenomenon wind farm owners are faced with a potential but uncertain risk of failure of wind turbines. Although modern wind turbines are designed according to the highest international and national standards, these codes where not intended to cover wind climates where strong typhoons occur[2]. As such application of these codes for wind turbine design in the Philippines may result in a higher risk. Technically speaking it is possible to design a wind turbine that can survive the most severe wind climate. However this special design implies high cost to wind farm owners and affects the viability of the project. As we all know wind farm projects are cost sensitive so that it is necessary that all costs should be minimized. The scenario would have been different if the "power source" can be controlled such that the annual income can be increased to offset the initial investment cost in mitigating typhoons. On the other hand one way to deal with the above problem is to accept the risk but be ready to obtain the necessary financial resources if the wind turbine towers will fail during a typhoon. This strategy however might lead to financial ruin when failures do occur. In view of the above it is therefore necessary that designers and owners jointly address important problems on possible failure modes of wind turbines in typhoon-prone areas. The failures include blade fracture, foundation overturning or tower buckling. In this paper the authors tackle the issue on tower buckling from the technical as well as from a financial point of view.

On the technical side only the buckling failure mode of the tower is considered since the failure cost is critical compared to blade failure. On the other hand it is intended that the foundation is stronger than the tower so that buckling of the tower occurs first before foundation overturns. In this case it has very small probability so this will not be considered. On the financial side the cash flow of a wind farm considering buckling failure is analyzed using stochastic capital budgeting analysis. The criteria used to assess the cash flow values are the net present value (NPV) or internal rate of return (IRR). The purpose of this technical-financial approach is to obtain an acceptable target probability of failure that satisfies a financial criterion that is acceptable to the owner. This approach allows the owner to make a conscious choice on the company's acceptable level of financial exposure corresponding to an acceptable target probability of buckling failure.

2. The probability of buckling failure of a wind turbine

The probability of buckling failure of a wind turbine tower due to typhoon loads in the Philippines has been previously analyzed by the same authors[3]. In this paper discussions on this topic are limited to the essential items needed in the cash flow analysis of a wind farm and interested readers are urged to refer to the details in the said paper.

Basically the probability of buckling failure or a wind turbine can be determined using the equation below

$$p_f = P[R(v) \leq S(v)] \tag{1}$$

where p_f is the probability of buckling failure, while $R(v)$ and $S(v)$ are the resistance and the IEC[4] wind load in terms of wind speeds, respectively. The statistics of the distributions in Eq. 1 have already been determined (as mentioned earlier) and are as follows: $\mu_{R(v)}$ = 89.22, $\sigma_{R(v)}$ = 12.36 m/s, $\mu_{S(v)}$ = 53.47 and $\sigma_{S(v)}$ = 7.28 while p_f = 6.4 x 10^{-3}. If the wind load includes typhoons and if the same quality of the wind turbine tower is required meaning p_f is maintained, then Eq. 1 will be modified into

$$p_f = P[R(v)_{new} \leq S(v')] \tag{2}$$

where $R(v)_{new}$ is the new resistance and $S(v')$ is the typhoon load. It is necessary to introduce a new buckling resistance of the tower since we want to assure the same performance of the wind turbine tower. We assume that a distribution $R(v)_{new}$ exists which satisfies Eq. 2. To simplify the analysis we assumed that it has the same distribution as $R(v)$ and the coefficient of variation $\delta_{R(v)}^{new}$ is equal to $\delta_{R(v)}$. Essentially this means that the probability density function of the resistance, denoted as $f_{R(v)}$, is shifted to the right with new mean $\mu_{R(v)}^{new}$ (see Fig. 1).

Another way of looking at this figure is that if the strategy is to accept the typhoon risk and "do nothing", then owner installs a tower with dimensions available commercially, e.g., diameter is 3.0 m with a thickness of 71 mm. This strategy is denoted as strategy 1 (see Table 1). However if owner wants to mitigate the typhoon risk by increasing the tower dimensions but maintaining the same probability of failure, then owner specifies a special design, e.g., diameter is 3.0 m with a thickness of 85 mm. This strategy is denoted as strategy 4. This strategy requires an added initial investment cost. If this added cost insignificantly affects the financial viability of the wind farm project then the owner may adopt this strategy.

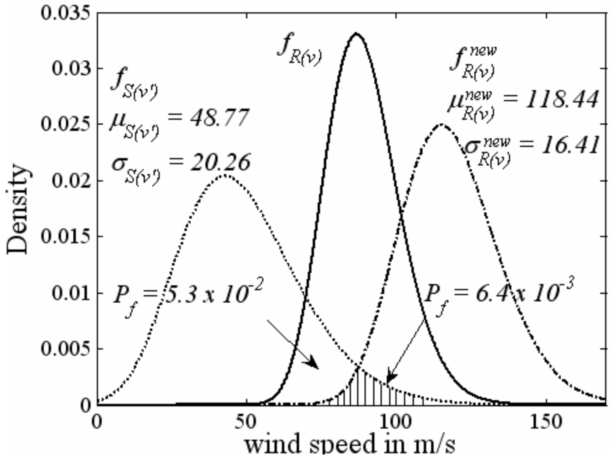

Fig.1 Load and resistance distribution

Table 1. Probability of buckling failure results

Strategy	dia. (m)	thick (mm)	mean	standard deviation	P_f
1	3.0	71	89.22	12.36	5.3 x 10^{-2}
2	3.0	76	99.67	13.81	2.6 x 10^{-2}
3	3.0	82	110.8	15.35	1.2 x 10^{-2}
4	3.0	85	118.44	16.41	6.4 x 10^{-3}

On the contrary if it significantly affects the economics of the project, then the owner may possibly look for other options (strategies 2 to 3) in favor of his financial viewpoint but with a lower probability of failure than strategy 1.

In this case how will the owner select the best strengthening strategy[5]? Since the options depend on the financial standing of the company this question will be answered later after looking into the economics of a wind farm.

3. Stochastic Capital Budgeting

When a power company decides to undertake new projects, it estimates how much capital is needed for the planned projects. The process by which a company decides which long-term investments add most value to the company is capital budgeting. The decision to reject a capital budgeting project depends on the analysis of the projected cash flows generated by the project throughout its service life. The cash flow (CF) is essentially the cycle of income (I) and expenses (E) of a project over its entire life.

$$CF = I - E \tag{3}$$

A cash flow projection model simply shows how much cash is expected to flow in and out of the proposed project for the entire plant life. In the succeeding sections the income and expenses of a wind farm are derived which will be utilized in the cash flow analysis.

To assess the project's cash flow value three major methods are used; the payback method, the net present value (NPV) and the internal rate of return (IRR) method. However because of the superiority of the last two methods over the first in terms of the accept-reject criterion, these two are adopted in this paper. Further both these methods use a discounted cash flow (DCF) analysis to rank a project or alternative by NPV or IRR.

3. 1 Income

There is a great deal of variation in the annual income of a wind farm. This quantity is dependent on the energy production of the individual units in the park that in turn is dependent on the wind speeds from year to year. However for cash flow analysis we can estimate the income generated by one turbine and multiply it with the k units to be installed at the site as shown below.

$$I = k \times AEP \times C_F \times A_F \times E_P \qquad (4)$$

The variable AEP is the annual energy production of one turbine in kWh, C_F is the capacity factor, A_F is the availability factor and E_P is the electricity price in monetary units per kWh. The AEP can be estimated using the long-term distribution of the 10-minute wind speeds (U_{10}) at the site and the power curve of the turbine. A Weibull distribution can best describe[6)] the distribution of (U_{10}) as shown below

$$F_{U_{10}}(u) = 1 - \exp[-(u/sc)^{sh}] \qquad (5)$$

where sc is the scale parameter and sh is the shape parameter. On the other hand, the power curve that indicates the electrical power outputs of a turbine at different wind speeds and shown in the equation below.

$$P_c = \begin{cases} 0 & \cdots \quad 0 \le U_{10} < 4 \\ 0.0031214U_{10}^4 - 1.5964U_{10}^3 + 41.855U_{10}^2 \cdots - 255.77U_{10} + 487.06 & 4 \le U_{10} \le 15 \\ 850 & \cdots \quad U_{10} > 15 \end{cases} \qquad (6)$$

Eq. (6) was modeled from an 850 kW wind turbine provided by a European wind turbine manufacturer. Therefore by simulating hourly wind speeds from Eq. (5) for one year substituting it to Eq. (6) the annual energy production can be estimated. Subsequently the annual income of the wind farm can be determined from Eq. (3).

3. 2 Numerical simulation of income

To describe the long-term distribution of U_{10} wind data taken from a wind mast with cup anemometers are utilized. Wind data recorded at 52 meters were selected because this almost corresponds to the height of the proposed wind turbine rotor axis. There were about 106,590 records with a mean wind speed of 8.69 m/s as shown in Fig. 2. These data are fitted to a Weibull distribution and the parameters determined using maximum likelihood method. The cumulative distribution and the probability density function of the Weibull fitting are shown in Fig. 3 and Fig. 4. Then by Monte Carlo simulation, U_{10} samples are simulated from the Weibull pdf. These samples are then used as input into Eq. 6 to obtain realizations of the power output.

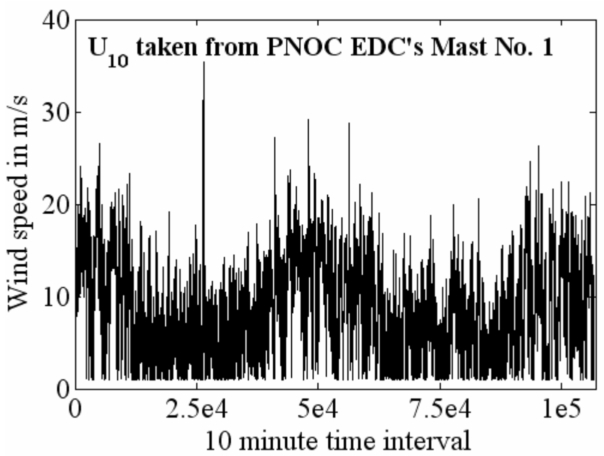

Fig.2 10-minute wind speeds taken at the site

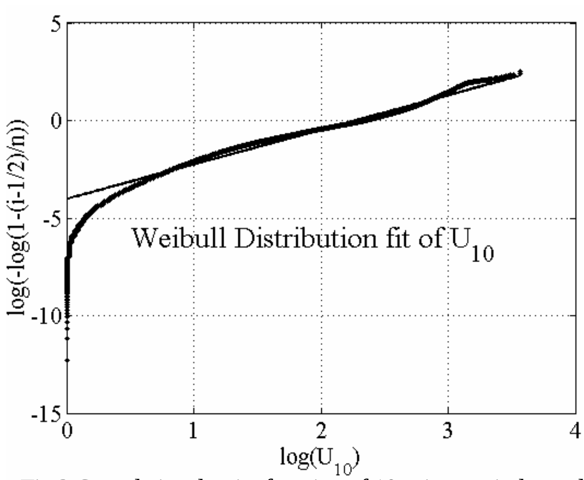

Fig.3 Cumulative density function of 10-minute wind speeds

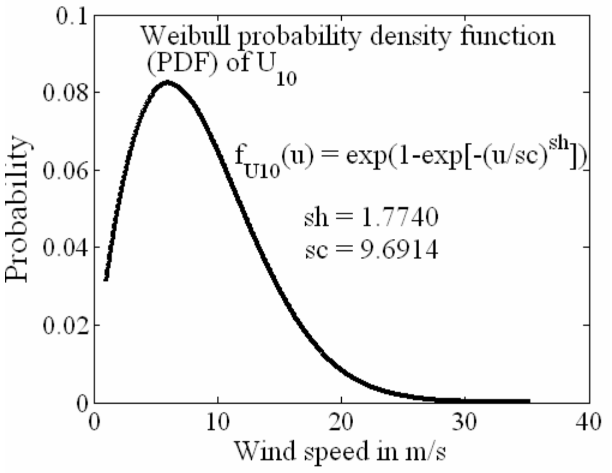

Fig.4 Probability density function of 10-minute wind speeds

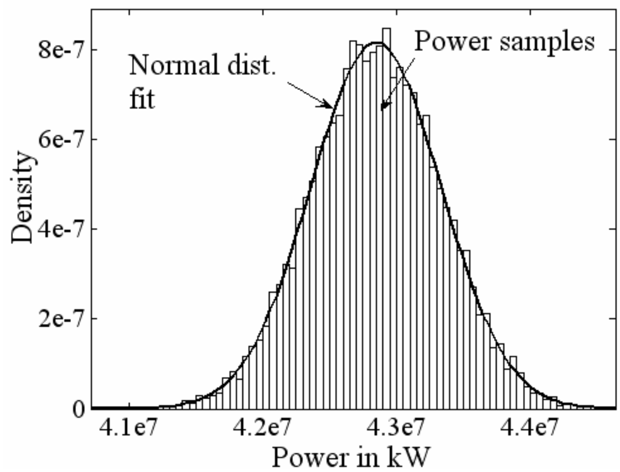

Fig.5 The pdf of the power output of a single wind turbine

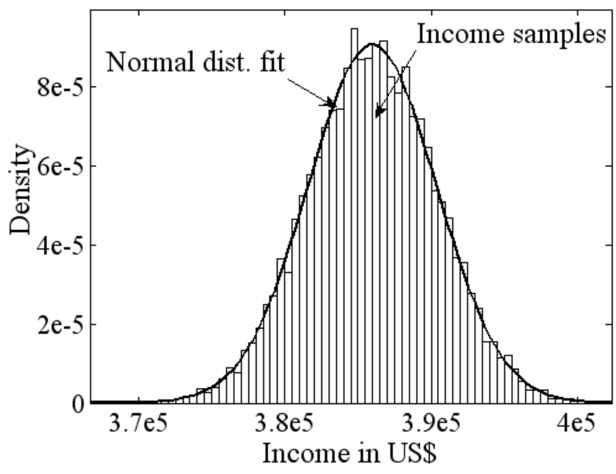

Fig.6 The pdf of the income of a single wind turbine

These samples are then used to estimate the pdf of the power output of a single turbine (see Fig. 5). Subsequently the pdf of the income can be estimated using Eq. 4 (see Fig. 6). The values of C_F, A_F and E_P used in the analysis are 0.30, 0.99 and 0.036 US$/kWh, respectively.

Table 2. Assumed cost values

Type of Cost	Value	Remarks
C_O	1479 US$/kW	Function of the installed capacity
$C_{O\&M}$	0.024 US$/kWh	Function of electric generation
C_R^1	182214 US$	t = 71 mm
C_R^2	194740 US$	t = 76 mm
C_R^3	209824 US$	t = 82 mm
C_R^4	217387 US$	t = 85 mm

3. 2 Expenses

The expenses of a wind farm consist basically of the following:

a. The initial investment cost C_o, which includes the wind turbine, infrastructure, capital costs, additional costs etc.

b. The operation and maintenance cost $C_{O\&M}$ of the wind farm for each year

c. The failure cost due to typhoon loss given as $PF_{j,T}^{i}(C_R^i + 0.5I_T)$. $PF_{j,T}^{i}$ is the probability that j turbines will fail (if strategy i is employed) on any T^{th} year during the service life of the wind farm, C_R is the reconstruction cost of the tower and $0.5I_T$ is the half year income of the turbine. It is assumed that it will take six months to reconstruct the wind turbine to full operational status.

Table 2 shows the value of each cost as used in the numerical analysis. In the reconstruction of the tower a markup of 20 percent was added to the full tower cost to cover installation and other added costs. The reconstruction cost is increasing since the basic cost of the tower increases due to changes in dimension to mitigate typhoon loss.

It is possible that a strong typhoon may occur on any year during the economic life of a wind farm. However to make the analysis realistic it is assumed that no more than one strong typhoon, that will cause buckling failure, will occur during the service period[7]. When this catastrophic event happens and there are four wind turbines in the farm then the following events are expected: E_0 = no turbine fails, E_1 = turbine no. 1 fails, E_2 = turbine no. 2 fails, E_3 = turbine no. 3 fails and E_4 = turbine no. 4 fails. Fig. 7 clarifies the above statements and how the probabilities of failure are applied for each year assuming a plant life of n years.

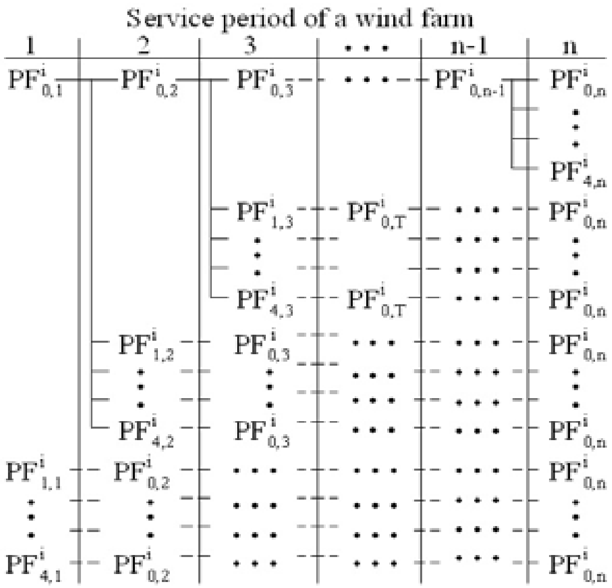

Fig.7 The application of the probabilities of failure for each year

Table 3. Probabilities of failure for each strategy

Strat	PF_0	PF_1	PF_2	PF_3	PF_4
1	7.8×10^{-1}	2.1×10^{-1}	1.7×10^{-2}	1.5×10^{-4}	7.9×10^{-6}
2	8.9×10^{-1}	1.0×10^{-1}	4.1×10^{-3}	7.1×10^{-5}	4.6×10^{-7}
3	9.5×10^{-1}	4.6×10^{-2}	8.0×10^{-4}	6.1×10^{-6}	1.8×10^{-8}
4	9.7×10^{-1}	2.7×10^{-2}	2.5×10^{-4}	1.1×10^{-6}	1.7×10^{-9}

To determine the values of $PF^1_{j,T}$ consider the probability of buckling failure for a single turbine given as 5.3 x 10^{-2} (Strategy 1) in Table 2. The authors assumed that the failure events are independent since the turbines are located at far distances from each other such that the failure of one turbine does not affect the other turbines. The combination of the failure of the turbines is however considered. With these conditions in mind, the probabilities of failure are calculated as shown below. The results for the other strategies are shown in Table 3.

1. Probability the 1 turbine will fail: $PF^1_{1,T}$ = 2.12 x 10^{-1}

   $P(E_1) = 5.3 \times 10^{-2}$
   $P(E_2) = 5.3 \times 10^{-2}$
   $P(E_3) = 5.3 \times 10^{-2}$
   $P(E_4) = 5.3 \times 10^{-2}$

2. Probability the 2 turbines fail: $PF^1_{2,T}$ = 1.69 x 10^{-2}

   $P(E_1 E_2) = 2.81 \times 10^{-2}$
   $P(E_1 E_3) = 2.81 \times 10^{-2}$
   $P(E_1 E_4) = 2.81 \times 10^{-2}$
   $P(E_2 E_3) = 2.81 \times 10^{-2}$
   $P(E_2 E_4) = 2.81 \times 10^{-2}$
   $P(E_3 E_4) = 2.81 \times 10^{-2}$

3. Probability the 3 turbines fail: $PF^1_{3,T}$ = 1.49 x 10^{-4}

   $P(E_1 E_2 E_3) = 1.49 \times 10^{-2}$
   $P(E_1 E_2 E_4) = 1.49 \times 10^{-2}$
   $P(E_1 E_3 E_4) = 1.49 \times 10^{-2}$
   $P(E_2 E_3 E_4) = 1.49 \times 10^{-2}$

4. Probability the 4 turbine fail: $PF^1_{4,T}$ = 7.89 x 10^{-6}

   $P(E_1 E_2 E_3 E_4) = 7.89 \times 10^{-6}$

5. Probability the no turbine fails: $PF^1_{0,T}$ = 0.77099

3. 3 Cash flow, Net present value and Internal rate of return

The stochastic income and costs have been developed in the preceding sections. These details of these costs are substituted into Eq. 3 so that the cash flow equation becomes

$$CF = \sum_{i=1}^{t} I_i - C_o - \sum_{i=1}^{t} C_{O\&M\,t} - \sum_{i=1}^{t} PF^i_{j,T}\, j(C^i_R + 0.5 I_T) \qquad (7)$$

The NPV is simply the summation of the present values of future incomes and expenditures[8]. It is quite easy to determine the NPV and requires three simple and nontrivial steps[9]. The first step is to determine the cash flow which is already given in Eq. 7. The second is to determine the discount rate r of the investment and the third is to calculate the NPV by discounting the cash flow using r to present values as shown in Eq. 8. If the NPV is positive then the company is making more money on the investment that it is spending on the cost of capital. However if the NPV is negative then the project is paying more in interest on the borrowed money than it making from the project.

$$NPV = \sum_{i=1}^{t} \frac{I_i}{(1+r)^t} - C_o - \sum_{i=1}^{t} \frac{C_{O\&M\,t}}{(1+r)^t} - \sum_{i=1}^{t} \frac{PF^i_{j,T}\, j(C^i_R + 0.5 I_T)}{(1+r)^t} \qquad (8)$$

Using identical discounting techniques, it is possible to calculate other financial indicators like the IRR which is the value of the discount rate that gives an NPV of zero[8] as shown below.

$$NPV = 0 = \sum_{i=1}^{t} \frac{I_i}{(1+IRR)^t} - C_o - \sum_{i=1}^{t} \frac{C_{O\&M\,t}}{(1+IRR)^t} - \sum_{i=1}^{t} \frac{PF^i_{j,T}\, j(C^i_R + 0.5 I_T)}{(1+IRR)^t} \qquad (9)$$

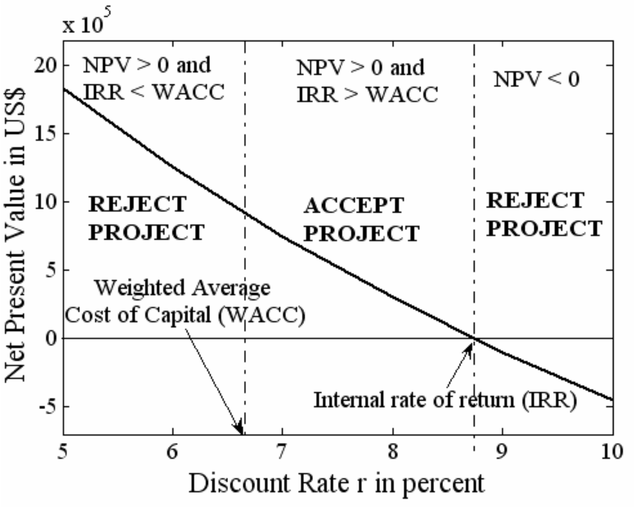

Fig. 8 Accept-reject criterion of project's cash flow

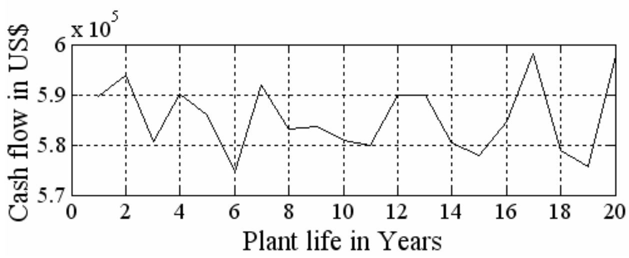

Fig. 9 Cash flow with no turbine failure

The IRR is an important index because it is the growth rate an investment project is expected to generate[10]. It can also be used to compare against the prevailing rates of return in the securities market or a company's overall required rate of return or the weighted average cost of capital (WACC)[11] on new investments. If the IRR exceeds this threshold rate then the investment is a good one otherwise the investment is not attractive. This reject-accept criterion is aptly shown in Fig. 8.

3. 4 Numerical simulation

To obtain results for the cash flow six sets of 20-year incomes were simulated. The expenses defined in the earlier section for different strategies were also calculated. For each strategy 600 cash flow results were obtained. Some of the results for Strategy 1 are shown in the succeeding figures. In Fig. 9 the cash flow is shown with no turbine failure. This figure shows how the cash flow fluctuates annually depending on the wind. In Fig. 10 there is a big drop in the cash flow after one turbine fails on the 5th year due to a strong typhoon. However as assumed earlier no more strong typhoons occur after this year so that no more failures occur after this event.

In Figs. 11, 12 and 13 it is a scenario wherein a strong typhoon hits a farm and two, three or four turbines fail. For each case these figures show the cash flow on that year, respectively. These figures also show the vulnerability of the cash flow of a wind farm in typhoon-prone areas.

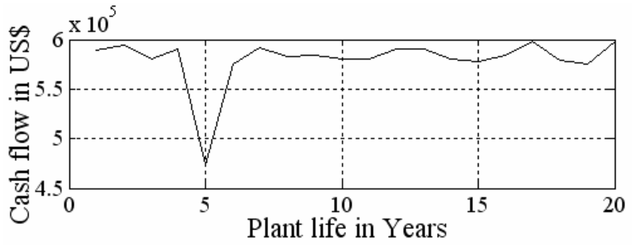

Fig. 10 Cash flow with one turbine failure on the 5th year

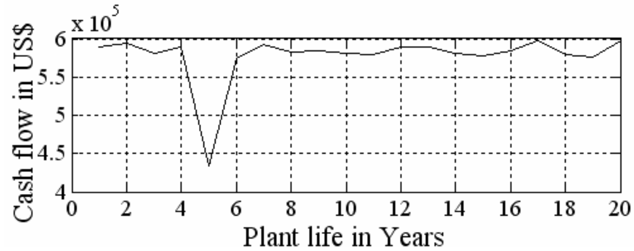

Fig. 11 Cash flow with two turbine failures on the 5th year

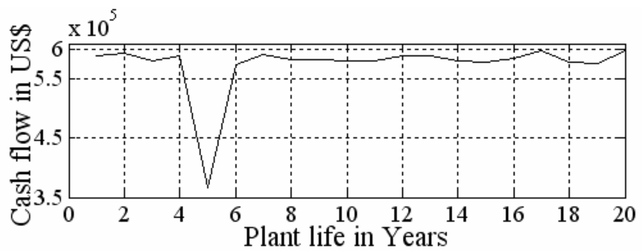

Fig. 12 Cash flow with three turbine failures on the 5th year

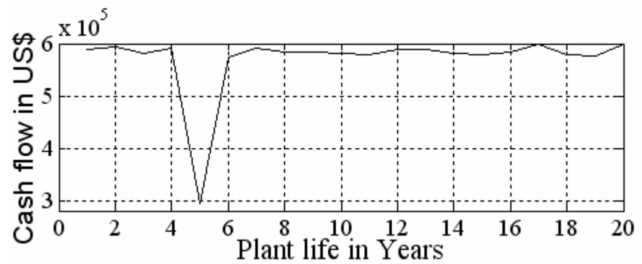

Fig. 13 Cash flow with three turbine failures on the 5th year

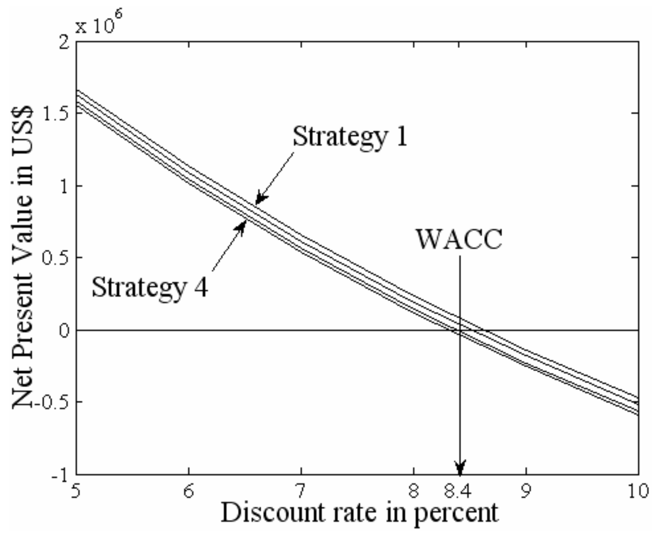

Fig. 14 NPV and IRR values of Strategies 1 to 4

Table 4. IRR result for each strategy

Strategy	P_f	IRR
1	5.3×10^{-2}	8.54%,
2	2.6×10^{-2}	8.43%
3	1.2×10^{-2}	8.31%
4	6.4×10^{-3}	8.24%

To assess the value of the cash flow results for each strategy Eq. 8 is applied with discount rates from 5 to 10%. Since there were 600 cash flow results for each strategy a total of a 6 x 600 NPV results were obtained. Subsequently the NPV results with the same discount rate are then grouped and averaged. The resulting averaged NPV values reduced to a 4 x 6 matrix, meaning 6 NPV values for each strategy. These results are then shown in Fig. 14. This figure shows that the NPV of the strategies are positive if the discount rate is less than 8.6%. It also shows that the NPV of Strategy 1 is highest but risks are higher if typhoon occurs. Strategy 4 has the lowest NPV among the four. This is quite logically since owner spends more to mitigate the risks of typhoons.

The IRR of the cash flows for each strategy were also calculated using Eq. 9. From the same 600 cash flow results a total of 4 x 600 IRR results were obtained. For each strategy the IRR was averaged and the results are shown in Table 4. The IRR of the strategies become meaningful if it is compared with an assumed WACC of a company. Assuming the WACC is 8.4% then Strategy 2 exceeds this rate and is financially attractive (see Fig. 13). In contrast, strategies 3 and 4 are lower that the WACC so these options are rejected.

From these results we can say that strategy 2 is the most favorable strengthening option with a target probability of failure equal 2.6×10^{-2}. On the financial side this strategy is also favorable to the owner since it satisfies the financial criteria of the company.

4. Conclusions

Buckling of wind turbine towers in typhoon prone areas in the Philippines is an issue that must be addressed by both designer and owners. Due to this the authors proposed an approach that satisfies technical as well as financial criteria. For the former a reliability analysis was used to obtain the target probability of buckling failure of the tower. This target value satisfies the reject-accept criterion of stochastic capital budgeting and is therefore financially favorable to the owner.

This proposed approach provides useful information for wind farm owners and designers to mitigate the buckling risks of wind turbines in wind farms due to typhoons.

5. Acknowledgement

The authors wish to thank the Renewable and Conventional Power Group of PNOC EDC for providing the wind data used in this paper.

References

1) Elliott, D., Schwartz, R., George, R., Haymes, S., Heimiller, G., Scott, G. and McCarthy, E.: "Wind Energy Resource Atlas of the Philippines", US National Renewable Laboratory, 2001.
2) Clausen, N. E., Ott, S., Tarp-Johansen, N. J., Norgard P., Larsen, X. G., Pagalilawan, E. and Hernando, S.: Design of Wind Turbines in an Area with Tropical Cyclones, Proc. of European Wind Energy Conference, Greece, 2006.
3) Garciano, L. E. and Koike, T.: A proposed typhoon resistant design of a wind turbine tower in the Philippines, submitted to the JSCE Journal of Construction Engineering and Management (under review), 2006.
4) IEC 64100-1, ed. 2, Wind Turbine Generator Systems – Part I: Safety Requirements, 1999(E).
5) Garciano, L. E. and Koike, T.: Managing the risks of a wind farm in typhoon-prone areas, Proc. of 10th East Asia-Pacific Conference on Structural Engineering & Construction, Kanok-Nukulchai, W., Munasinghe, S. and Anwar Naveed, eds. School of Engineering and Technology, AIT, Thailand, pp. 219 –224, 2006.
6) Ronold, K. O. and Larsen, G. C.: Reliability-based design of wind-turbine rotor blades against failure in ultimate loading, *Engineering Structures 22*, pp. 565 – 274, 2001.
7) Hoshiya, M., Nakamura, T. and Mochizuki, T.: Stochastic Asset pricing with seismic hazard risk, Journal of Engineering Mechanics, ASCE, Vol. 130, No. 7, pp. 780 –785, July 2004.
8) Burton, T., Sharpe, D., Jenkins, N. and Bossanyi, E.: Wind Energy Handbook, John Wiley & Sons Ltd., England, 2001.
9) http://www.odellion.com/pages/online%20community/NPV/financialmodels_npv_definition.htm
10) http://www.investopedia.com/terms/i/irr.asp
11) http://www.investopedia.com/terms/w/wacc.asp

(Accepted December 15, 2006)