International Institute for
Applied Systems Analysis
Schlossplatz 1
A-2361 Laxenburg, Austria

Tel: +43 2236 807 342
Fax: +43 2236 71313
E-mail: publications@iiasa.ac.at
Web: www.iiasa.ac.at

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Accelerating the Diffusion of Wind Power: An Analysis of Resistance Factors

Kenchi Kobayashi (kenchi@tgny.com)

Approved by

Leo Schrattenholzer (leo@iiasa.ac.at)
Environmentally Compatible Energy Strategies (ECS) Project

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Contents

Abstract

This paper describes the use of a combination of learning-by-doing (LBD) and benefit-cost analysis (BCA) using a Dynamic Programming method with stochastic assumption analysis to identify factors of resistance to the diffusion of wind turbine generators. To do so, we must take into consideration that there is a "waiting option" while – assuming the LBD concept in operation – the price comes down in a competitive market.

The application of the stochastic and dynamic programming model using real data on the diffusion of wind power generation in Germany, from 1990 to 2000, confirmed that the concept of the combination will affect the acceleration of diffusion of wind turbines where investors seek to optimize their investments to maximize their profit.

The model also suggests the risk of a vicious-circle retarding diffusion, especially with the "wait and postpone" decision method. Although the "wait and concentrate investment" decision method has the ability to allow investors to earn more effectively without negative effects for the diffusion, it only appears when there is sufficient manufacturers' ability to manufacture wind turbines. If there are low demands, there is always high risk of the vicious cycle of lower diffusion, no matter which decision method investors take. Effective countermeasures aiming at stimulating demands may be promoting wind technology as a good investment. We must analyze this vicious-cycle situation and establish the countermeasures by using subsidies, taxations, other regulations, and effectual investor relation (IR). The decision makers, responsible for making rules on taxations, subsidies, and other regulations, should take into consideration these effects which are caused by the application of the LBD.

Acknowledgments

The author is deeply indebted to Michael Obersteiner of the Forestry Program at IIASA, for his valuable comments concerning the "real option" and also for his useful suggestions on boundary conditions and the limiting conditions of the "waiting option".

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About the Author

At the time of writing, Kenchi Kobayashi was a senior researcher at Tokyo Gas Co., Ltd. For three months during the summer of 2003, he was a participant in IIASA's Young Scientists Summer Program, during which time he worked with the Environmentally Compatible Energy Strategies Program (ECS) under the supervision of Leo Schrattenholzer.

Accelerating the diffusion of wind power: An analysis of resistance factors

Kenchi Kobayashi

1. Introduction

To design an effective policy for the diffusion of renewable energy sources such as wind generation, one needs to take into consideration the costs reduction of the introduction of new technologies. For this we need an appropriate model to conceptualize trends in the economy and technological development.

Generally, costs reductions of new technologies are depicted by using the learning-by-doing (LBD) concept. Even though LBD uses different learning parameters to fit the cost reduction curves for each specific technology, it is well suited for predicting the costs reduction of new technologies as long as the learning parameters are known.

In an economical market, the decision will be made by means of a benefit-cost analysis (BCA). If we are to rely on economical mechanisms to diffuse new ecological generators, we must analyze the characteristics of BCA of investments in new technologies.

This paper presents the refinement of the classical BCA using the LBD concept in forecasting costs using a dynamic programming method with a stochastic assumption analysis. Generally, cost reductions as a result of technology development appear to have a positive effect for the diffusion of renewable energy, such as wind energy. If investors exercise a “waiting option”, however, cost reductions strongly impede diffusion, and sometimes create a vicious circle of both diffusion of wind turbine and monetary benefit of investment.

The results of the study presented here identify the factors that resist the diffusion of wind turbines and indicate how to reduce such resistance.

2. Overview of Conventional Studies

2.1. Learning-by-doing (LBD)

With many technologies at different stages of innovation and diffusion, the specific cost (US$/kW, which in this case is the price of wind turbine installation) of a technology gradually falls logarithmically as the cumulative capacity of this technology increases.

As long as the same technology is used (especially in wind turbine generation), the parameters of the cost reduction curve seem to be similar in different countries. While costs may differ in each country, this is only a reflection of the differences in the development stage of each country (Klaassen *et al*., 2002).

In the early stages of diffusion, real data closely follows the LBD curve, but at the matured stage, it sometimes induces uncertainty (IEA, 2001). This may be caused by the price strategy of wind turbine manufacturers used in the pricing of wind turbines (see Figure 1).

According to the conventional LBD theory, cost reduction is expressed by a decreasing-power law ($y = x^a$) just like other econo-physics phenomena. However, the early stage of costs reduction can be approximated by a logarithmic curve, too. In this study, simulation model is based on a logarithmical approximation. In a mature market, as costs tend to exhibit the character of price, the data does not appear to follow either a power function or a logarithmic curve.

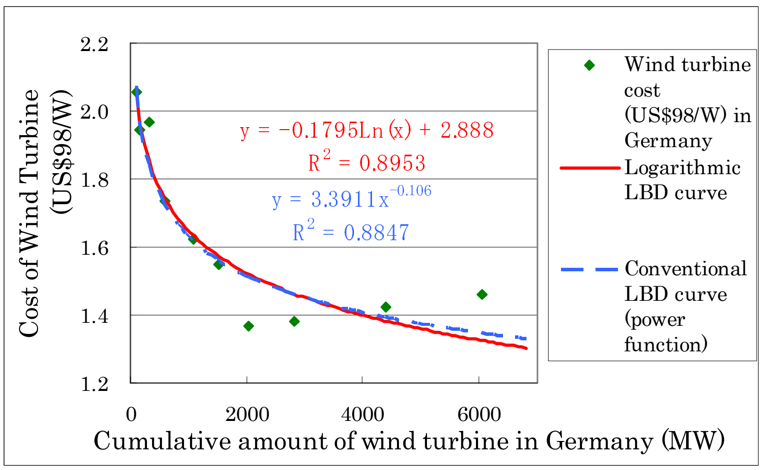


Figure 1: Costs reduction of wind turbines (US$98/kW) incrementally decreases with the cumulative amount of wind turbine (MW), approximated by "Logarithmic LBD curve" and "Conventional LBD curve (power function)". Data sources: EUWINet (ISET/CIEMAT), 2001; Rehfeldt, 2001; EWEA, 2001; IEA, 2001.

2.2. Benefit-cost analysis (BCA)

When taking into consideration how investors make decisions, we would need to know how they decide, and when and how much they invest. In a competitive market economy, investments are categorized as profitable or not profitable. Typically investors make their decisions using a benefit-cost analysis, and if an investment is deemed not to be profitable, it will not be made.

In a classical benefit-cost analysis, cost reductions are usually ignored as random effects. This may mislead investors to postpone making investments into new technologies and keeping costs at a higher level than if investments were made. The classical decision method may therefore cause investors to miss opportunities to make money. At the same time, consumers also lose in economical and environmental terms. Because of this, the benefit-cost analysis needs to be modified in order to combine it with the LBD method. Figure 2 displays the classical benefit-cost analysis, while Figure 3 illustrates the decision method when using the classical benefit-cost analysis.

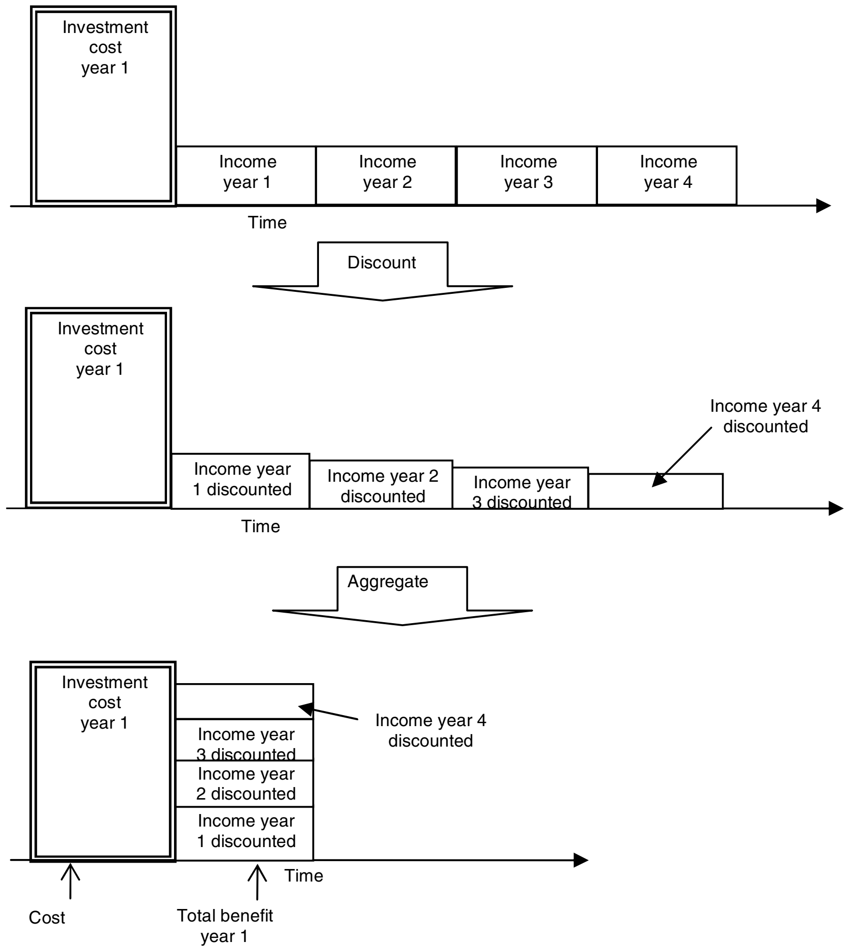


Figure 2: Classical benefit-cost analysis. If investments cost exceed the total benefit in year 1, the classical benefit-cost analysis recommends that the investor should not invest.

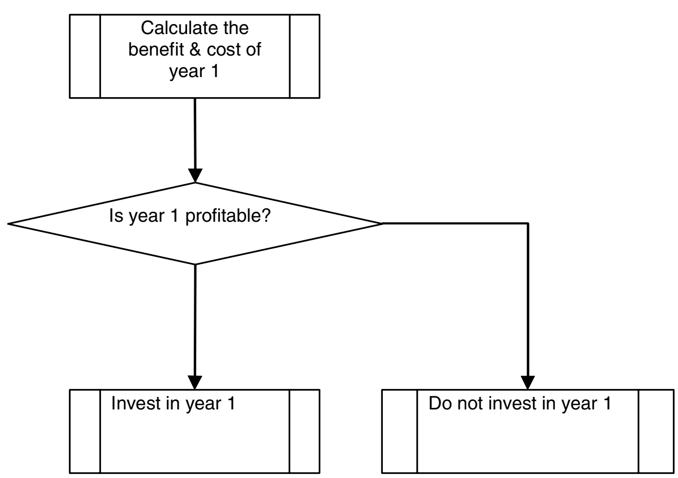


Figure 3: Flow chart of a classical decision method based on a benefit-cost analysis.

3. Combination of LBD and BCA

In this section, we describe the basic concepts of combining learning-by-doing (LBD) and benefit-cost analysis (BCA) step by step for the diffusion of wind turbines. We begin by examining the characteristics of the LBD concept from an investor's point of view.

The investments of an individual year can be calculated using a dynamic program by estimating the cumulative amount of wind turbine capacity (MW) up until the year where we want to know how the investments would turn out. The investor knows the cumulative capacity of wind turbines (MW) produced for the previous year as a statistical value, but can only estimate the value for the following year. If there are no other investors, his investment in this year (year 1) and cumulative capacity of wind turbines for this year (year 1) would make the cumulative capacity of wind turbines for the following year (year 2). In other words, this means he could predict the investments for the following year with a high level of confidence using this LBD formula. This situation, the "non-competitive (dominated) market", is described in more detail in Section 3.1.

With other competitors involved, the cumulative amount of wind turbines produced for the consecutive year is a summation of the following three factors. The first is the cumulative amount of wind turbines produced up until last year, the second is the increase in wind turbines owing to an investor's investment, and the third is that of other investors. In a pure competitive market the third factor would be unknown. Hence, we have to envisage the possible investments of other investors in order to calculate the investments for the following year. This "competitive market", in which other investors exist, is described in Section 3.2. Finally in Section 3.3, the investment options when an investor holds back his investment is presented and explained with two alternatives: "wait and postpone" and "wait and concentrate investment" decision methods.

3.1. Non-competitive market

In a non-competitive market, the combination of LBD and BCA is easy to understand. The concept behind the combination is the aggregation of more than one year's benefit and cost (e.g., a minimum of 2 years)

1. Assume year 1's investment, and calculate year 1's benefit and cost.
2. Using the LBD formula, assume year 2's investments per kW based on year 1's investment.
3. Assume year 2's investment, and calculate year 2's benefit and cost.
4. Discount year 2's benefit and cost to adjust to year 1.
5. Add the discounted cost and benefit of year 2 to that of year 1.
6. Subtract the cost from the benefit. If benefits exceed costs, investment is recommended as profitable.

The key element of this combination is Step 2: the assumption using the LBD formula based on year 1's investment. This combination can only be applied when a convincing forecast is made regarding future costs reductions, as with LBD. Otherwise, investments made in the first year are a risky gamble. Although there may be losses in the initial year of investment, investors need to consider a time period beyond one year (i.e., 2 years). We also consider the fact that “costs reductions in the following year (year 2) depend on the amount of investments (i.e., sacrifice) during this year (year 1)”.

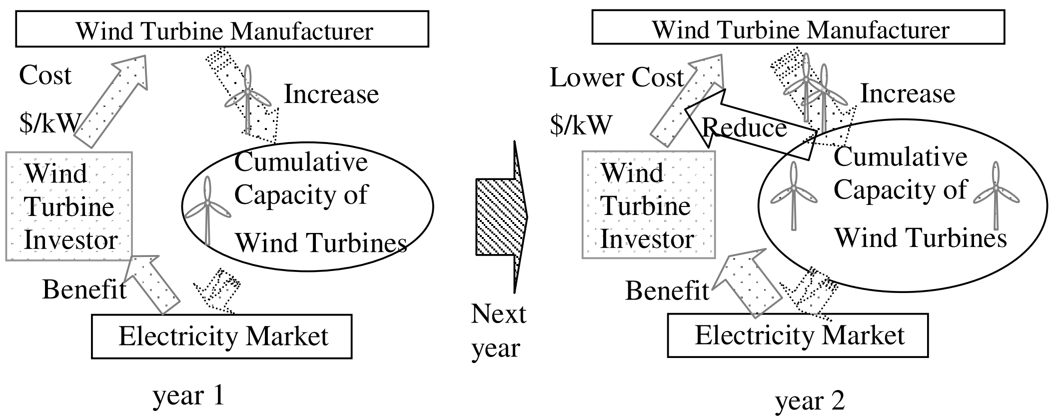


Figure 4: Schematic diagram of how costs reductions work in a non-competitive market as a cycle. According to the learning by doing, costs reductions of the wind turbine occurs along with the increase of the cumulative capacity of the wind turbine, that accelerates investment for it, investment increases cumulative capacity again.

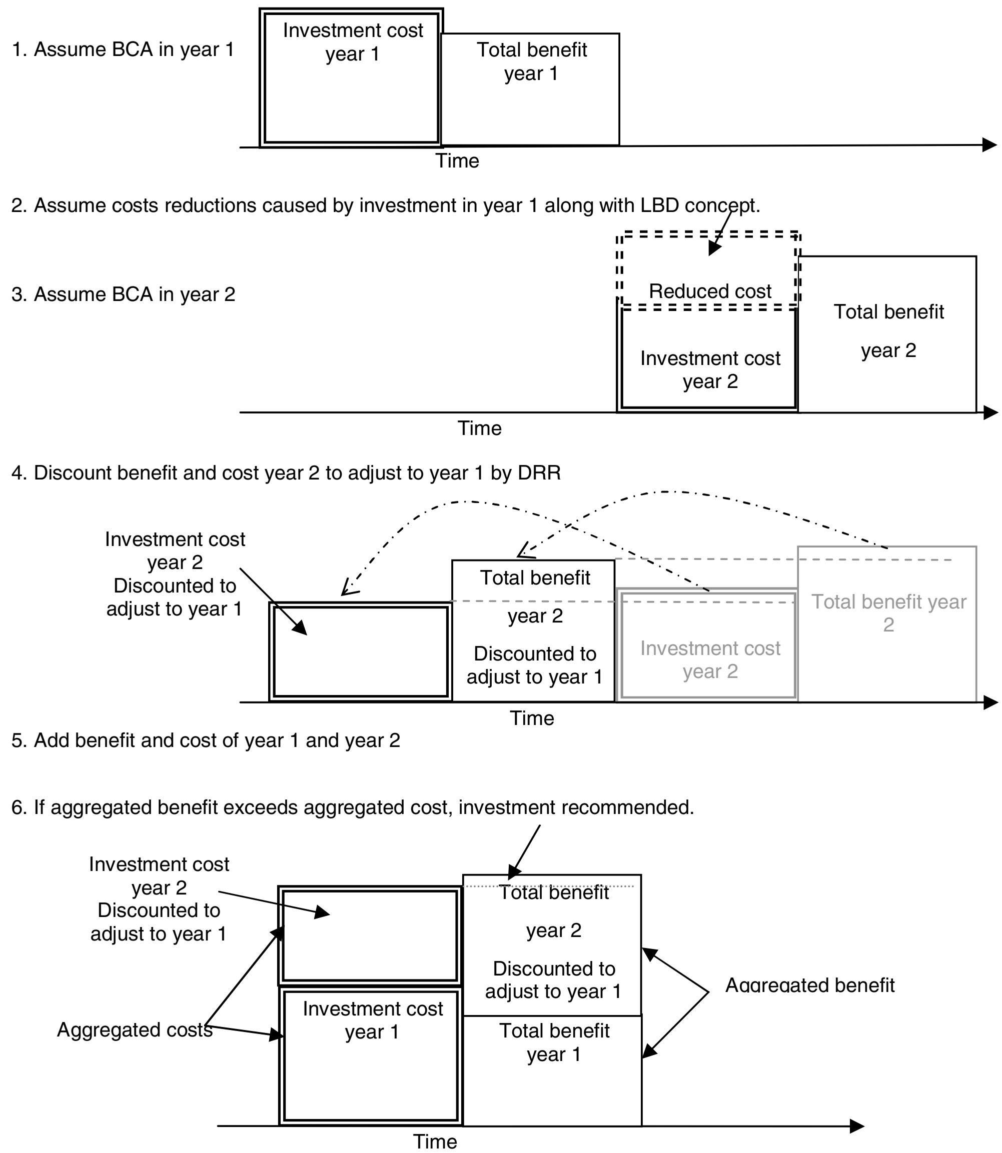


Figure 5: Combination of LBD and BCA in a non-competitive market. Even though no profits can be gained in year 1, an investor may invest if the aggregation of benefit and cost in plural years is profitable. In this figure, the minimum of 2 years is shown.

In general, however, as there is only a positive feedback factor, the combination of LBD and BCA appears to have the potential to create an endless cycle for the diffusion of new technology, such as wind turbine generation, in non-competitive markets.

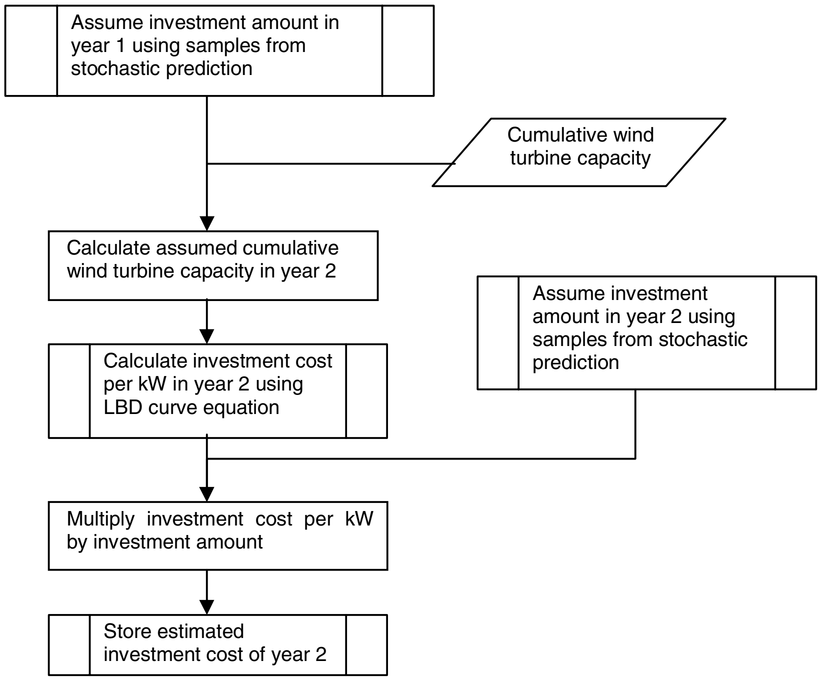


Figure 6: Estimation of investments of the following year (year 2) using LBD with a dynamic programming method.

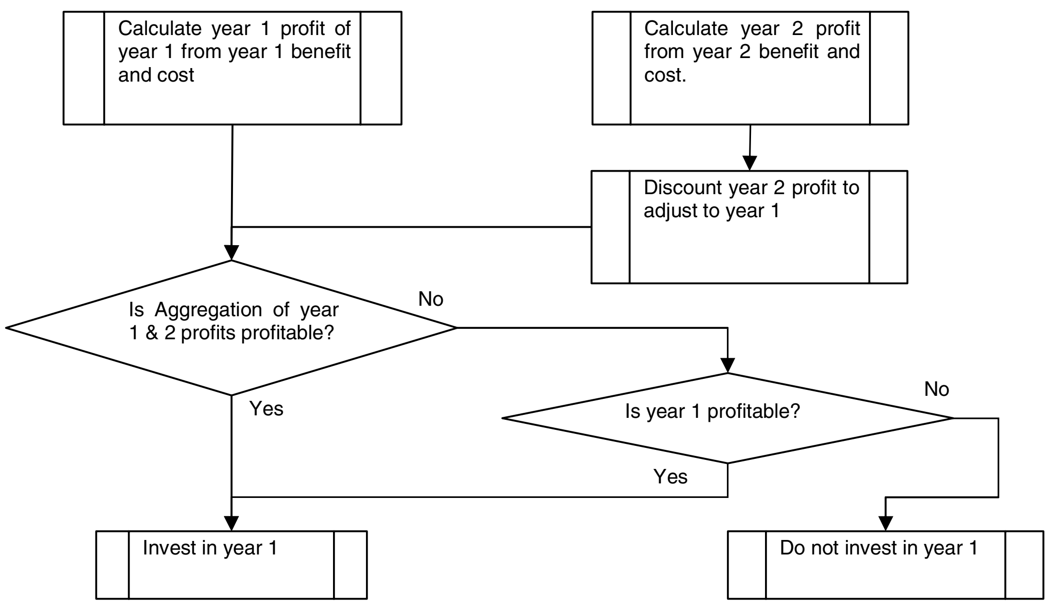


Figure 7: Flow chart of the decision method based on the combination of BCA and LBD in a non-competitive market. In this chart, the minimum number of years is two. However, the concept of combination is not restricted to two years.

3.2. Competitive market

In a competitive market, there are many competitors, though they may also cooperate to achieve specific costs reductions of wind turbines. It is obvious that it is much less effective for one investor to spend money on an investment in wind turbines than for two or more investors to do the same. Generally, costs reductions as a result of increased cumulative capacity appear to be a good thing for the diffusion. However, the costs reductions of wind turbines with other investors may act as a deterrent to invest. This is because an investor can postpone his investment for a year or more to wait for a reduction in costs owing to other investors' investments. If an investor could predict the costs reductions using the LBD concept while just waiting for the cumulative amount of wind turbines to increase as a result of investments by other investors, then he could hardly decide whether he should invest in a year or not.

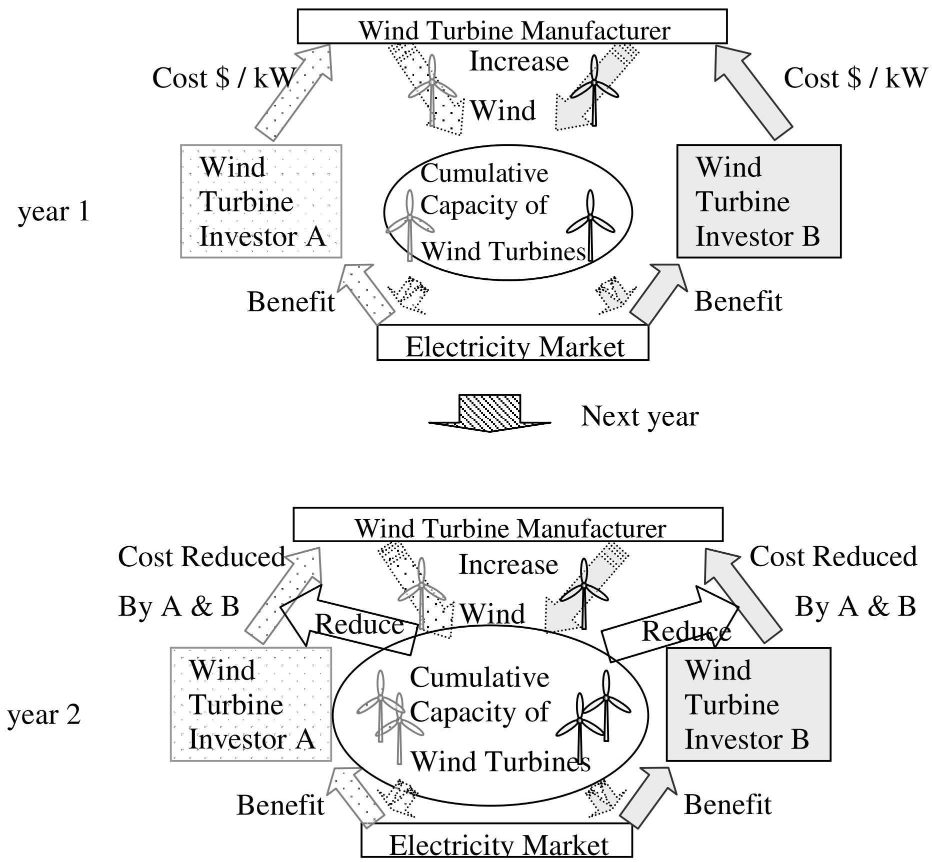


Figure 8: In a competitive market, investors have to consider the investment amount of a rival investor in order to estimate the aggregated amount of the cumulative capacity of wind turbine in year 2 which will decide the reduced cost in year 2.

This should be treated as a problem of the kind described by the "real option" method, called the "waiting option" (Trigorgis, 1996). This factor may act as a negative feedback, so we have to take it into consideration in the wind turbine diffusion model. To consider the effect of this, the following steps will be applied in this paper:

1. Divide aggregated plural years' benefit and cost into Investor A's and Investor

B's benefit and cost.

2. Extract each investor's benefit and cost.
3. If one investor waits for a year, he can earn a much better return at a much lower risk, without the sacrifice of investment in year 1.

In the calculation for year 2, we have to estimate the other investor's investment in year 1 to estimate year 2's product costs using the LBD formula. There is a variety of possibilities regarding the assortment of investments by investors. So the investor has to consider the competitor's strategy to decide his own strategy, as in a game theory. This problem should be solved as a stochastic dynamic program.

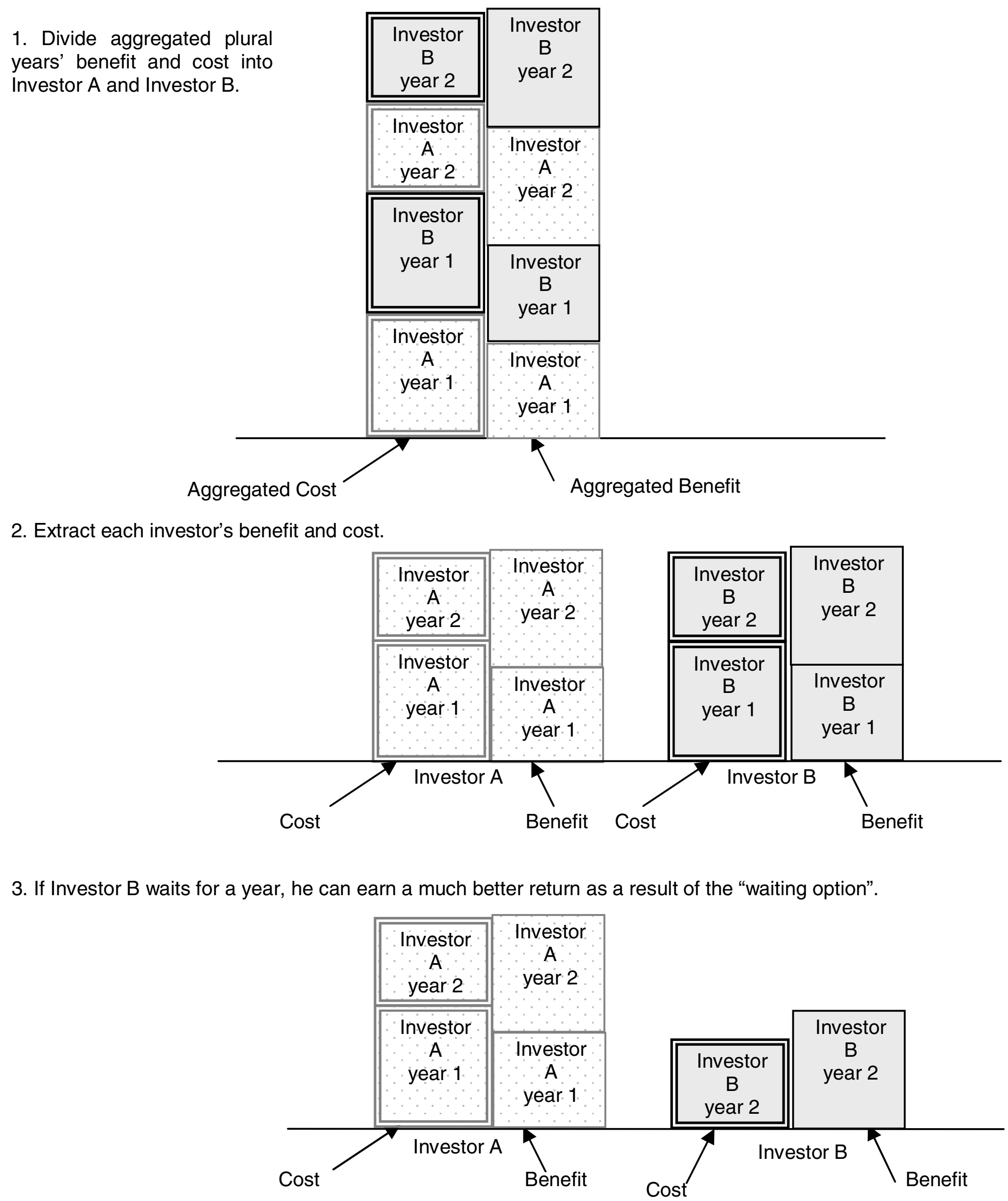


Figure 9: Combination of LBD and BCA incorporating the investor's "waiting option".

The “waiting option” may allow an investor to earn more money. However, this may delay the diffusion of wind turbines and sometimes the diffusion falls into a vicious circle, in which, both investors may wait until the other invests in order to earn more, thus the classical chicken or egg question may occur.

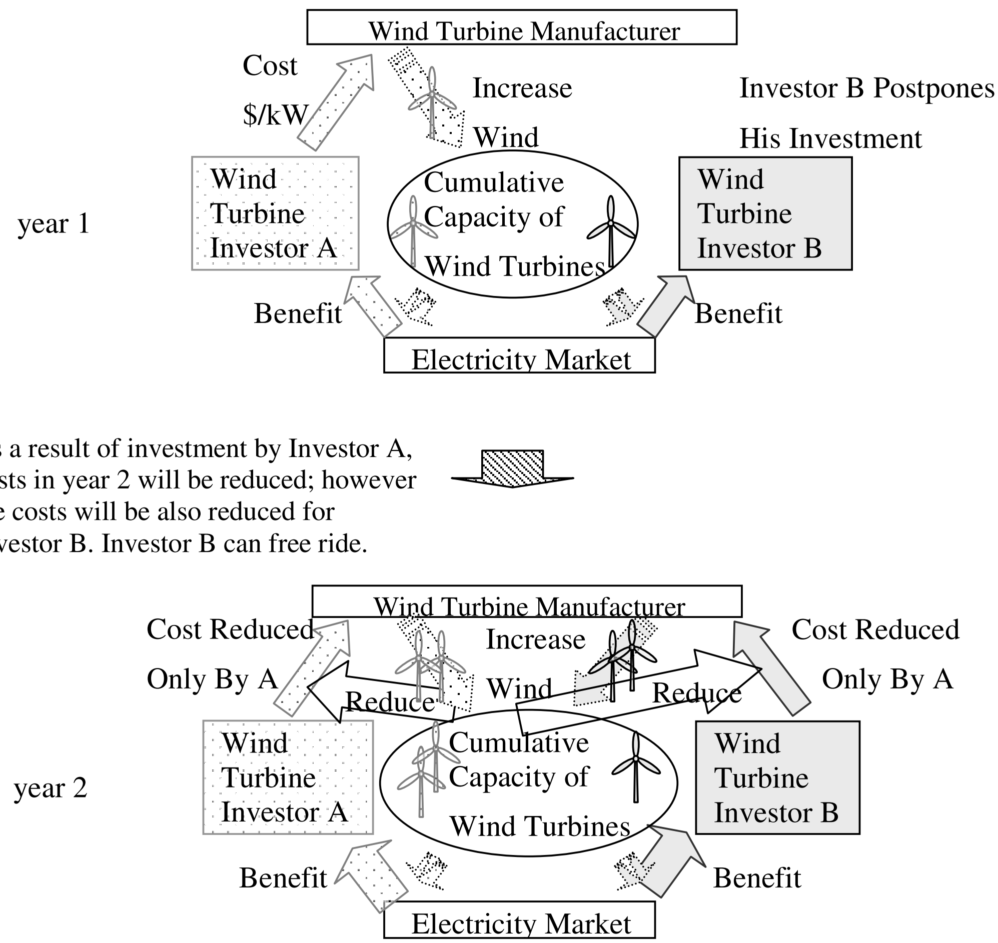


Figure 10: Schematic graph of how the waiting option method occurs in a competitive market. Investor B postpones his investment using his “waiting option”, Investor B can “free ride” the costs reductions by the investment of Investor A.

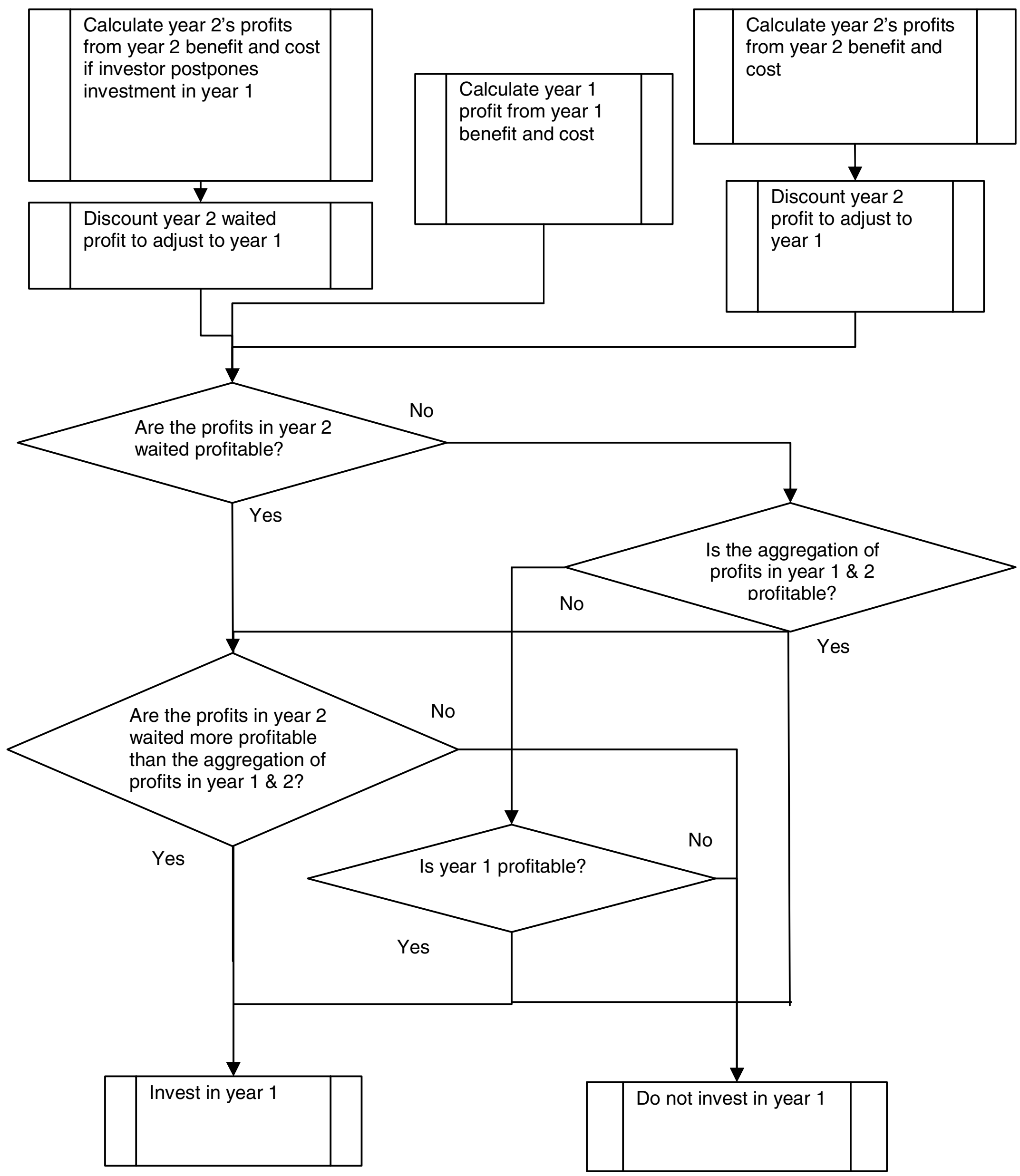


Figure 11: Flow chart for the decision method based on the combination of BCA and LBD in a competitive market. To calculate profits for year 2 and profits for year 2 waited, one must estimate the other investor's investments in year 1 so that one can predict the investment costs of year 2 using the LBD concept.

3.3. "Wait and concentrate investment" concept

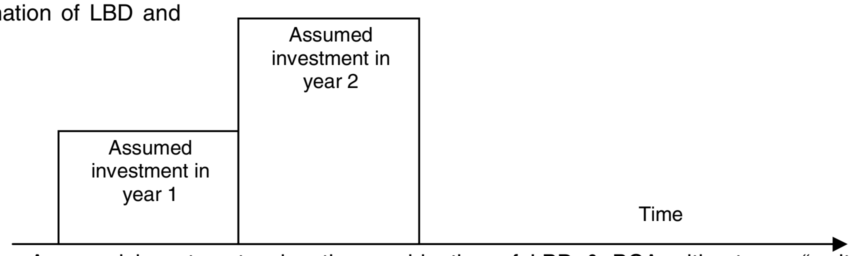
How many wind turbines the investor plans to build in the second year is also a problem. The investors could afford to make the total investment of year 1 and year 2 at the same time but only in the second year, provided that they deferred their investments in the first year (i.e., “wait and concentrate investment”). In this case, the waiting effect might be strong enough to postpone the investment in the first year, and sometimes these decisions lead to a vicious circle of waiting for each other’s investment than the ordinary “wait and postpone” concept because the investment amount in year 2 (based on the “wait and postpone” decision method) is the same amount of the previously assumed amount of the year 1. In contrast, the investment amount in year 2 (based on the “wait and concentrate investment” decision method) permits the investment of the aggregated amount of the previously assumed amounts of year 1 and year 2. As the costs decline, year 2 is always more efficient and the year 2 investment of the “wait and concentrate investment” is larger than “wait and postpone”, the likelihood of “wait and concentrate investment” entering a vicious cycle is stronger than the “wait and postpone” method, as long as the fully aggregated amount from the previously assumed amount of year 1 and 2 investments. However, if the investment in year 2 is adjusted to the proper amount, there is always a possibility not to postpone. The first step is to assume the increase in wind generation capacity which has been postponed until the next year to equal the capacity originally planned for the first year (“wait and just postpone”). For more details, see Appendix A.

The second step also concerns “wait and concentrate investment”. In the second year, investors can afford to invest the total amount of the first and second year’s investment at one time. In this paper, the second year’s investment is the sum of the prior year 1 investment and multiplied by the prior year 2 investment with a concentration ratio. The concentration ratio is assumed to be flexible between 0 to 100% and stochastic. For more details, see Appendix B. Using an optimization process, the proper amount of waiting and concentration will be described in Section 5.

3.4. Other limitations

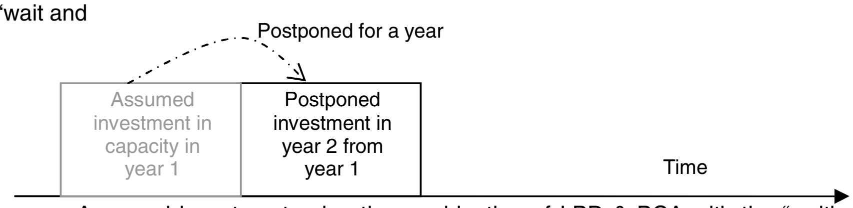
Wind turbine construction capacity also acts as a powerful constraint for the diffusion of wind turbines. If an investor wanted to invest in wind generation in excess of the construction capacity, he would not be able to install the wind turbines that he wanted. His installation is limited to the wind turbine construction capacity.

A. Combination of LBD and BCA



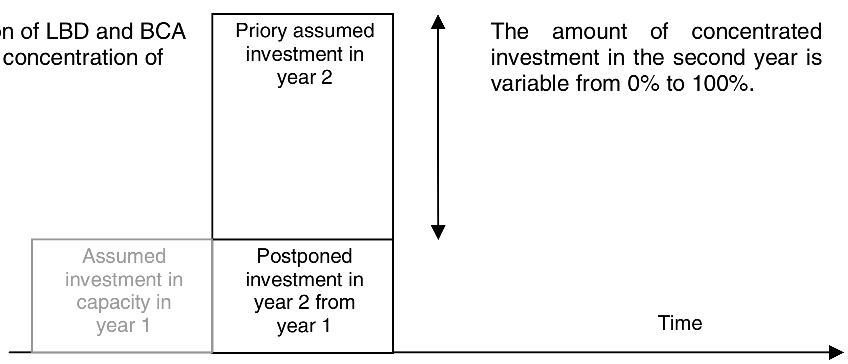
- Assumed investment using the combination of LBD & BCA without any "waiting option".

B. Combination of LBD and BCA with "wait and postpone"



- Assumed investment using the combination of LBD & BCA with the "waiting and postpone" option.
- Capacity is simply postponed from year 1 to year 2.
- The combination effect will thus not appear in this waiting case.
- The waiting effect is analyzed in this pattern of postponement in Section 4.

C. Combination of LBD and BCA with "wait and concentration of investment"



- Assumed investment using the combination of LBD & BCA with the "wait and concentration investment" option in year 2
- The amount of capacity is calculated as the total capacity of that postponed from year 1 to year 2 and the formerly assumed amount of the increase in year 2.
- Invest in year 2 at one time enables investor to earn more. But in year 2, if investor thinks about year 2 and year 3, he can earn more when he investments in year 3 at one time, so he will postpone his investment in year 2 again. This means he can't investment forever, and he can't earn money.
- There must be optimized amount of the concentrated investment in year 2, thus consider it as variable from 0 to 100% to adjust the optimized amount of investment.
- This pattern of investment will be considered in Section 5.

Figure 12: Comparison of the assumed amount of investment in year 2 with the three options: "no waiting", "wait and postpone" and "wait and concentrate investment".

4. Simulations with Alternative Assumptions

4.1. Overall modeling

The modeling of the combination of LBD and BCA is based on historical data for the German wind generation developments from 1990 to 2000. German data were selected because Germany has adopted the strategy of using market mechanisms to diffuse renewable energy, even though the wind generating companies were subsidized to a large extent by electricity companies in the form of higher feed-in prices than other generators. The German strategy has been highly effective in diffusing wind power generation, even though some overload of the subsidy payment has been forced on electricity companies near the seashore, where there is much wind and many of the wind turbines were constructed (JAPIC, 2003).

Even using real data, the stochastic model is built to analyze the risk of an investment decision. Simulations were run with either the Latin hyper cube method or Monte Carlo method. Learning by doing is a phenomenon of time dimension and the model should have time axis. The "Dynamic Programming" method is introduced to analyze the effect of annual amount of investments and capacity of wind turbines which is a key factor of LBD.

In this study, the competitive market has been discussed. Each competitor is interpreted as a group and only the total investment of each group is used to estimate the amount of increase of capacity and monetary profit in a year. For the analysis, the number of investors is set at two: Investor A and Investor B. For more information about this modeling and simulation, see Appendix A.

4.2. Rectangular distribution of decision management parameter

In this section we consider the basic case where there is no optimization by investors. In this case, the amount of investment will be a rectangular distribution as explained below.

4.2.1. In a competitive market

There are wind turbine manufacturers as a supply side, and wind turbine investors as a demand side. There are assumed to be three or four sizes of average wind turbine supply capacity on the manufacturer's side. The lowest level is 0.4 times of the wind generation cumulative capacity in that year. The highest level is equal to the cumulative capacity in that year. In addition, capacities of 0.6 and 0.8 (in some cases 0.7) times are also simulated. Each wind turbine investor (utility) decides how much to invest according to a rectangular distribution (lower limit: 0, upper limit: as below).

Investors' average investment budget is also assumed to be at three levels. The highest demand level is twice the average of the ability to supply side, the middle demand level is nearly equal to the average ability to supply side, and the lowest demand level is half of the average ability to supply side.

In these situations, manufacturer's supply capacity has a major effect on diffusion. As the supply capacity increases, diffusion and profit increase are nearly parabolic in all cases. Where LBD and BCA are combined with a waiting option having a negative feedback effect, on the other hand, Investor A's cumulative profit increases only when demand exceeds or is comparable to supply capacity.

Provided that the investments follow a rectangular distribution, the combination of LBD and BCA have some merit for investors as a means of earning more profit. However, it also has a negative influence on the diffusion of wind turbine generators when investment demands exceed supply.

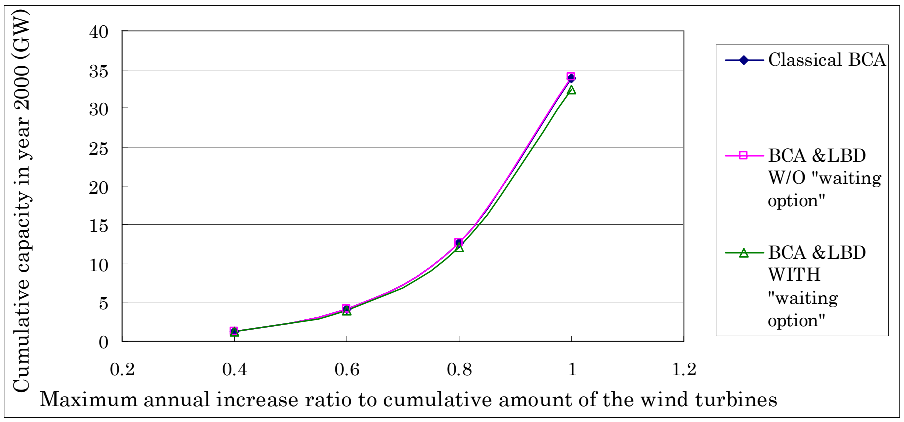


Figure 13: Cumulative total capacity of Investor A for the year 2000 simulated since 1990 provided that the investment follows a rectangular distribution. The investment demand to supply capacity ratio is 2:1.

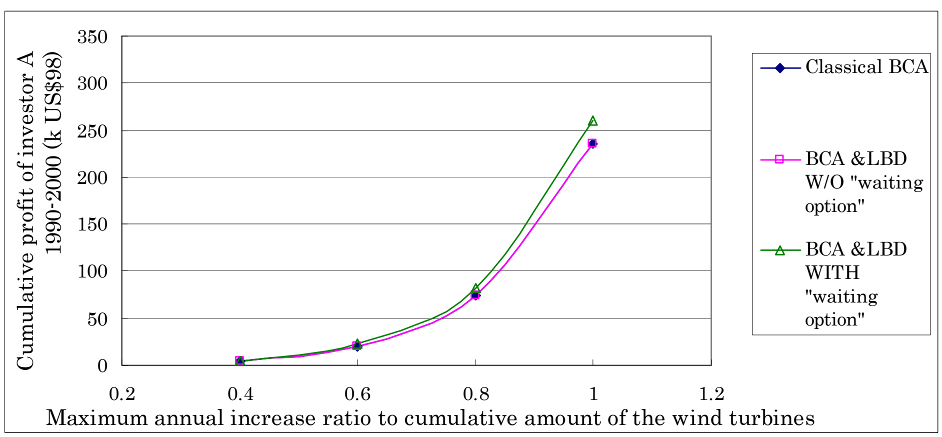


Figure 14: Cumulative profit of Investor A from 1990-2000 simulated since 1990 provided that the investment follows a rectangular distribution. The investment demand to supply capacity ratio is 2:1.

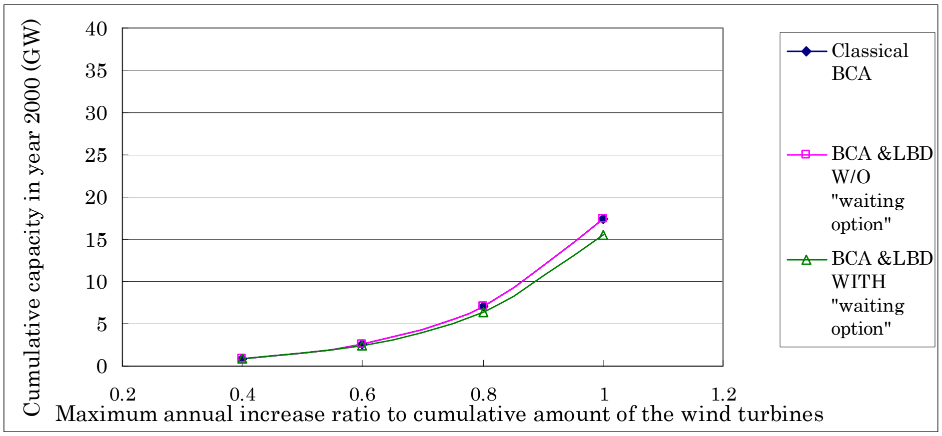


Figure 15: Cumulative total capacity of Investor A in 2000 simulated since 1990 provided that the investment follows a rectangular distribution. The investment demand to supply capacity ratio is 1:1.

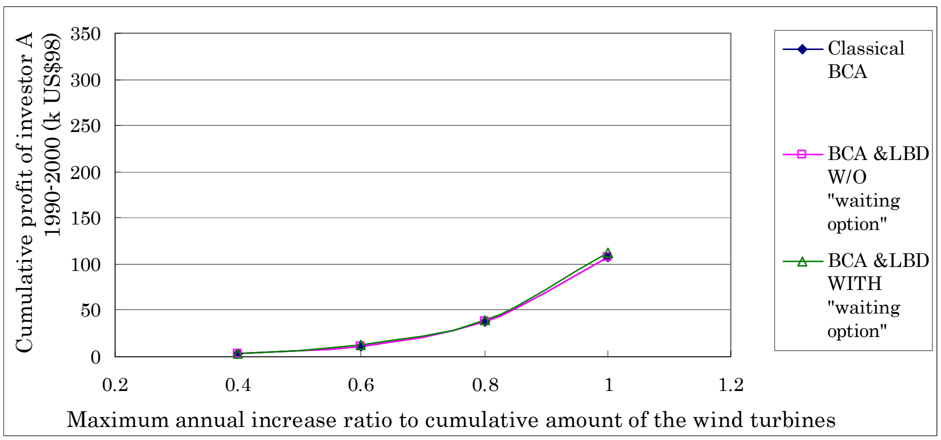


Figure 16: Cumulative profit of Investor A from 1990-2000 simulated since 1990, provided that the investment follows a rectangular distribution. The investment demand to supply capacity ratio is 1:1.

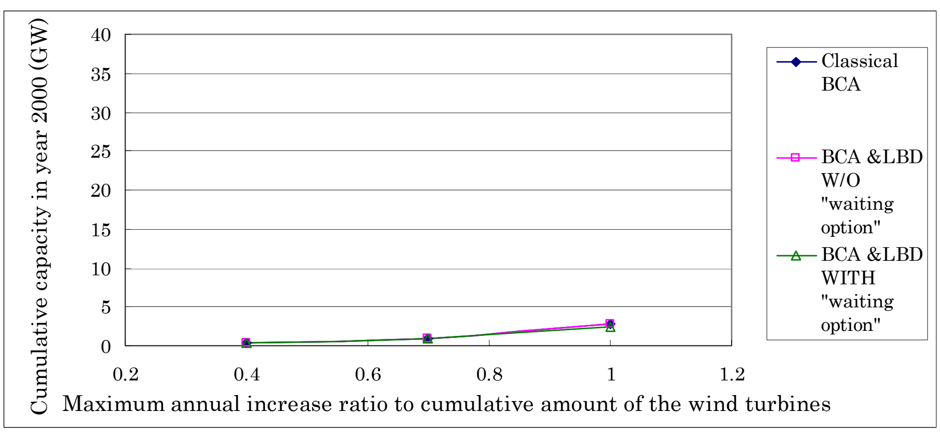


Figure 17: Cumulative total capacity of Investor A in 2000 simulated since 1990, provided that the investment follows a rectangular distribution. The investment demand to supply capacity ratio is 0.5:1.

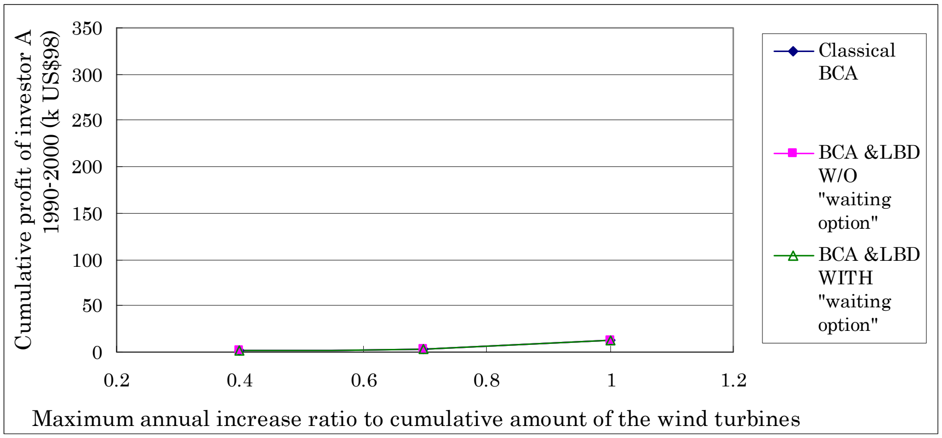


Figure 18: Cumulative profit of Investor A from 1990-2000 simulated since 1990, provided that the investment follows a rectangular distribution. The investment demand to supply capacity ratio is 0.5:1.

4.2.2. In nearly dominated markets

In this paper, we do not simulate the case of a pure dominated market, but simulate nearly dominated markets. The investment ability of Investor A in relation to Investor B is assumed to be 1:1, 1:0.1, and 1:0.01. However the total ability of the investment is adjusted to the same total value. The average wind turbine supply capacity on the manufacturer's side is assumed to equal wind turbine capacity already installed in the year, which permits an annual doubling of construction if demanded. In other words, the maximum annual increase ratio for the cumulative amount of wind turbines is fixed at 1.

If the amount of increase of investment owing to Investor B is always small, Investor B's decision is expected to have no influence on Investor A or diffusion of wind turbines. However, the simulation generates an unexpected result. Generally, the balanced budgets of the investors (1:1) lead to a more effective diffusion of wind turbines and more profit for the investors. This means that two big groups of competitors seem to have an accelerating effect on diffusion assuming a rectangular distribution of investment.

According to the simulation under the assumed wind turbine diffusion, the combination of LBD and BCA without the waiting option has very little effect on increasing diffusion and the profits of investors in each situation. Moreover, the waiting option has a strong negative feedback character even in the "1:0.01" situation as well as the "1:0.1" situation. The dominated company earns much, but the effectiveness of investment (cumulative profit of Investor A (US$98)/cumulative capacity of Investor A (MW)) shows that a more dominated situation decreases the effectiveness of investment. Even in this situation, the combination of BCA and LBD earns much more than the classical decision-making method. This may mean that where the investment follows a rectangular distribution, the investor tends to use the combination of LBD and BCA with the waiting option.

In other words, when Investor A uses the waiting option in a market dominated by Investor A, this option acts as a significant resistance factor. And the domination itself is the strong resistance factor for the diffusion of wind turbines. However, the waiting option acts as a positive factor for increasing his profits and the effectiveness of investment (see Figs. 19-22).

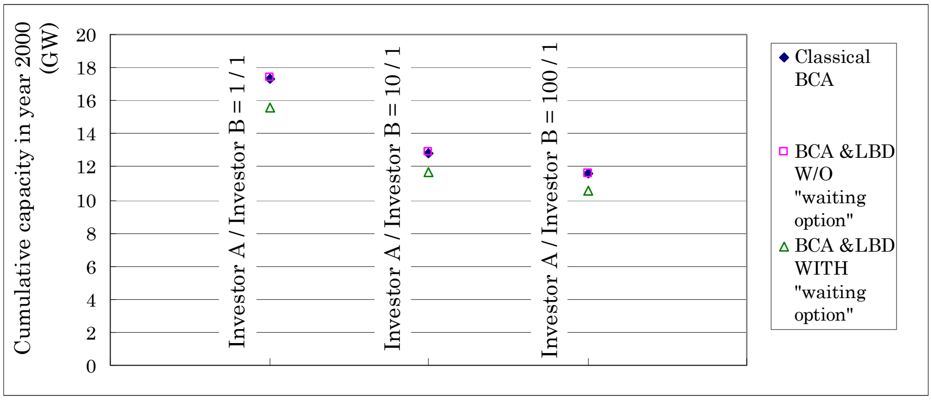


Figure 19: Cumulative total capacity in 2000, simulated since 1990, in competitive and nearly dominated markets provided that the investment follows a rectangular distribution. The investment demand to supply capacity ratio is 1:1. Maximum annual increase ratio of cumulative amount of wind turbines is 1.

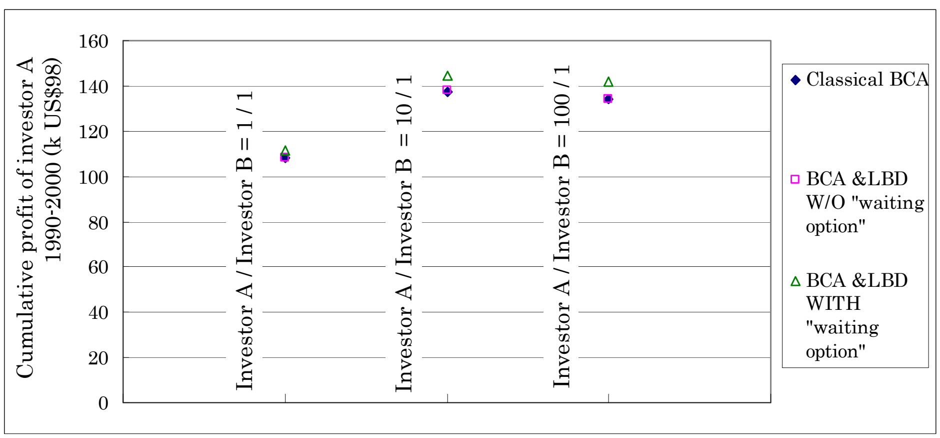


Figure 20: Cumulative profit of Investor A 1990-2000, simulated since 1990, in competitive and nearly dominated markets provided that the investment follows a rectangular distribution. The investment demand to supply capacity ratio is 1:1. Maximum annual increase ratio of cumulative amount of wind turbines is 1.

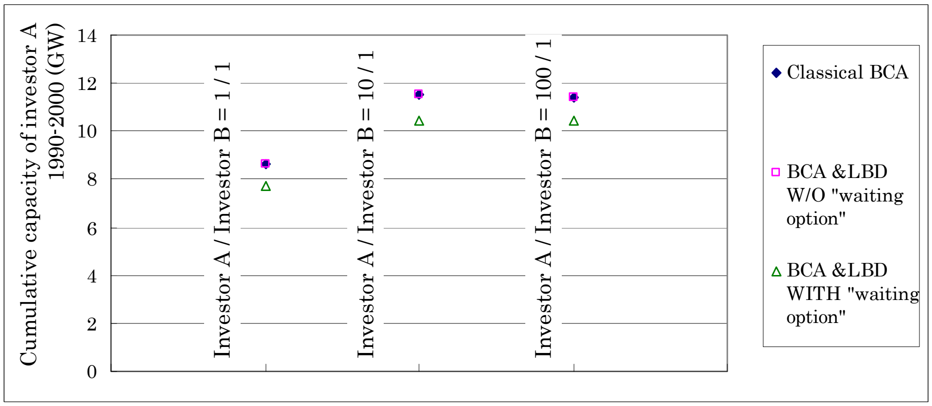


Figure 21: Cumulative capacity of Investor A in 2000, simulated since 1990, in competitive and nearly dominated markets provided that the investment follows a rectangular distribution. The investment demand to supply capacity ratio is 1:1. Maximum annual increase ratio of cumulative amount of wind turbines is 1.

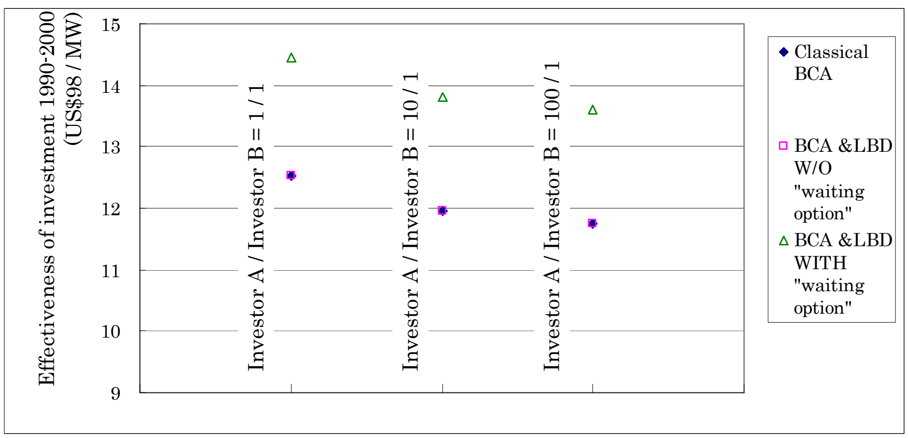


Figure 22: Effectiveness of investment from 1990 through 2000 in competitive and nearly dominated markets provided that the investment follows a rectangular distribution, simulated since 1990. The investment demand to supply capacity ratio is 1:1. Maximum annual increase ratio of cumulative amount of wind turbines is 1. The competitive market shows the most effectiveness of the investment.

4.3. Optimized decision management parameter

Using sensitivity analysis, it is easy to understand that the more investments can not only earn the more returns but also earn at the lower risks. Checking with an optimizing simulation in addition confirms that investors always tend to afford their upper limit of the investment probability criteria of the model. So if wind turbine investors (utilities) optimize their investments to maximize their profit, they will tend to shift the distribution so that it no longer follows a rectangular distribution. Even though optimization shows the merit of upper limit investment, there are still limitations to investment budgets. To simulate optimized situations, the distribution should have shifted character to the upper limit investment.

In the following sections, the probability of investment is described by Weibull distributions. Each distribution has the same average, but the larger number of shape parameters shifts the shape towards higher investment. A higher shape parameter represents a more convinced and stable will of investors to keep investing. As Investors A and B are assumed to be groups of investors, the distribution of Investors' budget may be described by a normal distribution applying the law of large numbers. In this paper, however, the number of investors included by Investor A or B is assumed to be not large enough for this law to apply, so that the distribution of Investors are not assumed to be a normal distribution. In this case, whether the selection of decision method is effective needs to be considered. See Appendix C for Weibull distribution.

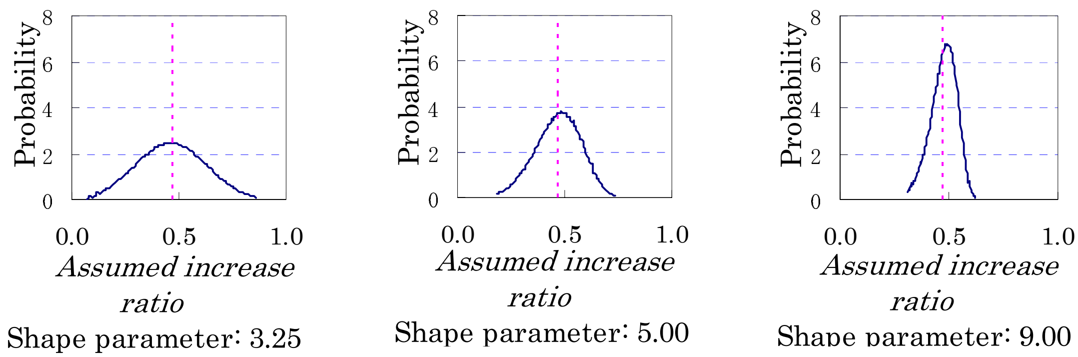


Figure 23: Assumed Weibull distribution of an Investor's budget. Distribution has approximately same average; in these cases, they are 0.466. However the modes and variances are different according to the different shape parameters. Shape parameters are as follows. Left: 3.25 (symmetrical to average value), Middle: 5, Right: 9. The increasing shape parameter shifts the modes to the higher investment and the more concentrated to the modes as follows. Left: 0.466, Middle: 0.484, Right: 0.487.

4.3.1. In a competitive market

In this subsection, the situation is similar to that described in section 4.2.1. However, the probability of investment is different, even though their average values are the same. The demand/supply ratios were at two levels: 1:1 and 2:1. The shape parameter of the Weibull distribution is simulated for three levels: 3.25, 5, and 9. When the shape parameter is 3.25, the Weibull distribution is symmetrical to the average. Even though the average of the investment distribution is the same value, both the average cumulative capacity and the average cumulative profit of Investor A are different from each other. Generally, a right-skewed investment peak (this means a larger shape value) will have a good impact both on diffusion of wind power and investors' profits, but the differences are negligible after the shape value exceeds 5.

Unlike a rectangular distribution, a non-rectangular distribution such as a Weibull distribution has a very low impact on diffusion and profits relative to basic BCA. Regarding diffusion, cumulative total capacity will be increased a little using a combination of BCA and LBD. In every shape parameter, the BCA and LBD with the "waiting option" decision has a slightly negative feedback effect on the diffusion of wind turbines. The larger number of the shape parameter tends to gain more capacity even when the average is the same, however, more than 5 makes only a small difference.

In every shape parameter, the difference of decision method is very small in the aspect of the investor's profit. The larger number of the shape parameter tends to gain more profits even when the average of the investment budgets are the same, however, more than 5 makes only a small difference.

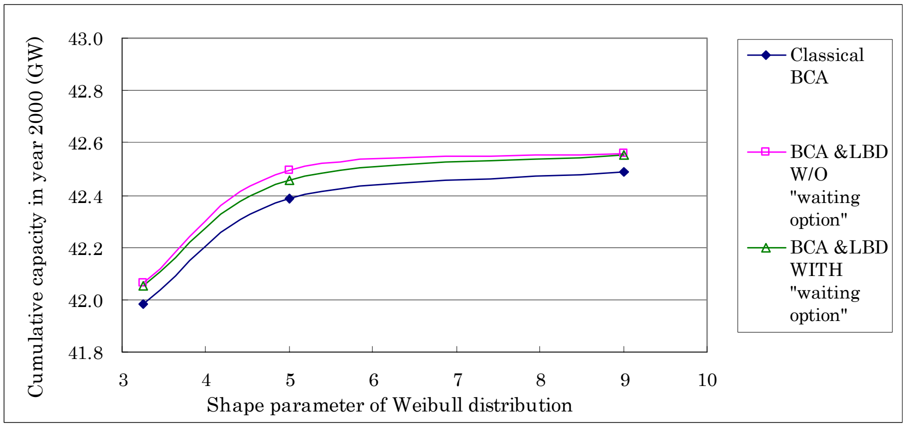


Figure 24: Difference of cumulative capacity when changing the shape parameter of Weibull distribution of investors' investment budget, in GW, in year 2000, simulated since 1990, the investment demand to supply capacity ratio is 1:1. Maximum annual increase ratio of cumulative amount of wind turbines is 1.

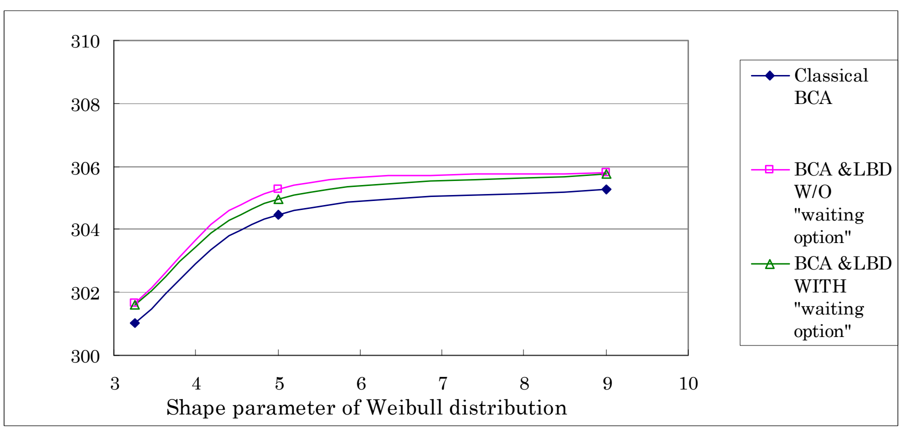


Figure 25: Difference of cumulative profits of Investor A when changing the shape parameter of the Weibull distribution of the investors' investment budget, in kUS$98, for 1990-2000, simulated since 1990, the investment demand to supply capacity ratio is 1:1. Maximum annual increase ratio of cumulative amount of wind turbines is 1.

4.3.2. In a dominated market

In this subsection, we again describe a nearly dominated market as in section 4.2.2, but the probability of investment is different even though their average values are the same. The shape parameter of the Weibull distribution is simulated with one shape parameter level, i. e., 9. With the rectangular distribution described in section 4.2.2, the combination of LBD and BCA had no significant effect on the diffusion of wind turbines, though the waiting option increases the profits to investors significantly. With the optimized distribution, by contrast, there are no significant differences between the decision methods even in profits. The effectiveness of investments (cumulative profit of Investor A, given in US$98)/(cumulative capacity of Investor A, given in MW) are very similar in both methods. Also in the optimized situation, the balanced budgets of the investors (1:1) lead to a more effective diffusion of wind turbines and profits for the investor. This means that the existence of too many competitors seem to create resistance to diffusion even with the Weibull distribution of investment. Even using Weibull distribution, a competitive market tends to diffuse more than a dominated market. However too many investors also seems not optimal for the diffusion of the wind turbines.

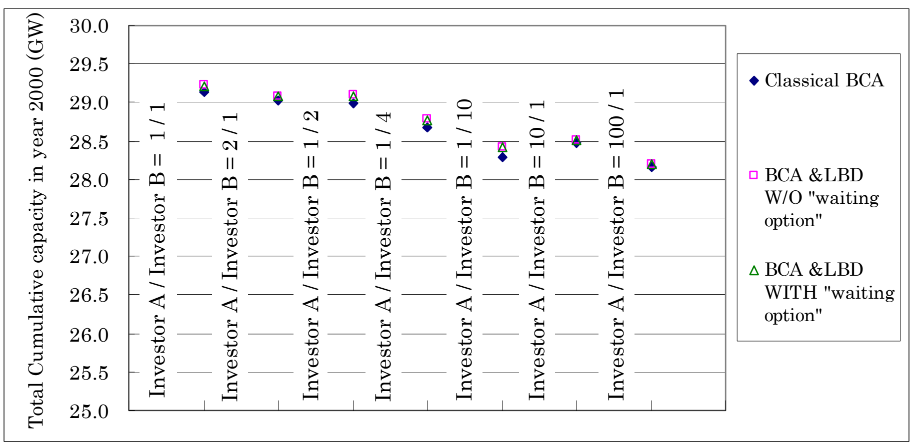


Figure 26: Total cumulative capacity of wind turbines in competitive and nearly dominated markets, in year 2000, simulated since 1990, the investment demand to supply capacity ratio is 1:1. Maximum annual increase ratio of cumulative amount of wind turbines is 1. Investment probability is Weibull, shape parameter is 9.

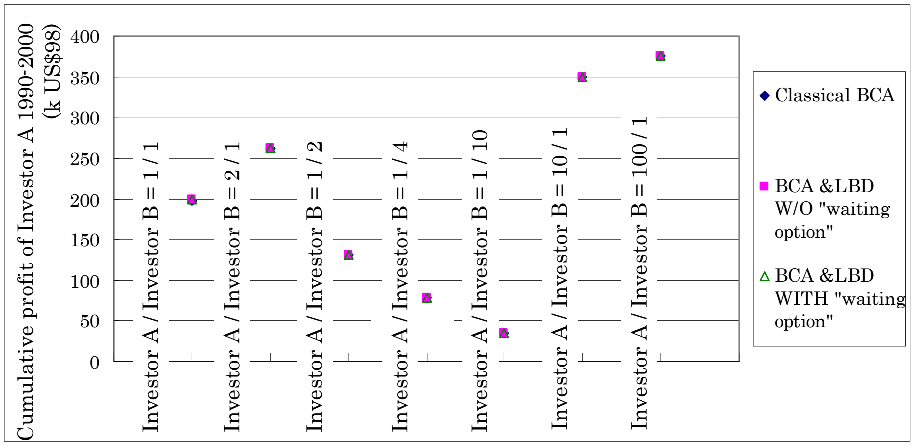


Figure 27: Cumulative profits of Investor A in competitive and nearly dominated markets, in 1990-2000, simulated since 1990, the investment demand to supply capacity ratio is 1:1. Maximum annual increase ratio of cumulative amount of wind turbines is 1. Investment probability is Weibull, shape parameter is 9.

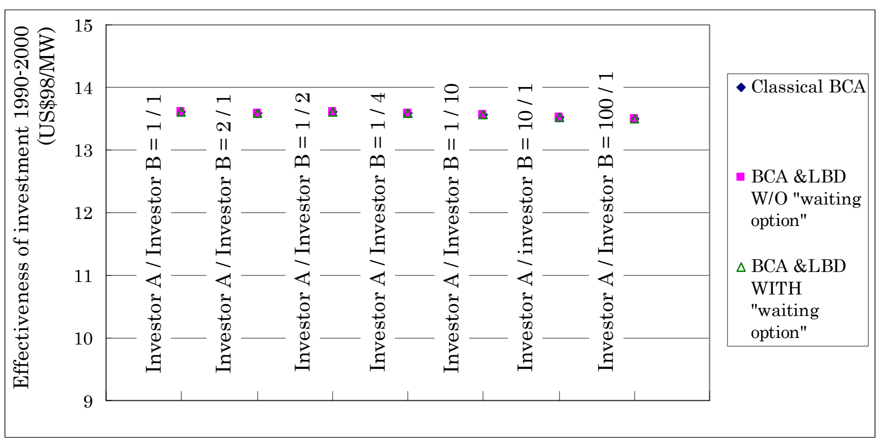


Figure 28: Effectiveness of investment of Investor A in competitive and nearly dominated markets, for 1990-2000, simulated since 1990, the investment demand to supply capacity ratio is 1:1. Maximum annual increase ratio of cumulative amount of wind turbines is 1. Investment probability is Weibull, shape parameter is 9.

An investor's profit increases as his market share increases. This makes him dominate the market if he can. But Figure 26 shows that the dominated market is not suitable for the diffusion of wind turbines. These characteristics do not depend on the decision method when investors use the Weibull distribution. When investors use the Weibull distribution for investment budgets, there are no significant differences in the effectiveness of investment.

5. The "Wait and concentrate investment" Method

In Section 4, we found that the effect of the combination of LBD and BCA depends on the capability of the manufacturer of wind turbines, the distribution of the investment probability, and their average values. However, this applies only to decisions where investments are only postponed by one year. In other words, it changed only investment timing from year 1 to year 2, while the amount of investment of the prior planned year 1 and conclusively decided investment amount of year 2 is the same amount.

In this section, the maximum amount of the investment in year 2 when the investor decides to postpone his investment in year 1 by year 2 is assumed to be the aggregation of the prior planned investment amount for year 1 and that of year 2, only later is it multiplied by the "concentrate ratio" (see bottom of Figure 12.).

5.1. Description of the "wait and concentrate investment" method

If an investor makes a maximum investment in year 2 by this method (concentration ratio: 1), the investment will nearly always be postponed and the diffusion of wind turbines will never occur. Fortunately, in this case, the cumulative profit of the investor is also nearly zero, and so the investor will not take this decision only according to the maximization of profit for himself. This means there should be some optimized parameters for the "concentration ratio" in year 2 to maximize profit even though these parameters might be different from the parameters to maximize the diffusion of wind turbines. For precise notation and equations, see Appendix B.

5.2. Results of "wait and concentrate investment" decision method

As the distribution of the maximum annual increase ratios were tuned for the "wait and concentrate investment" method, a direct comparison of these results with those described in Section 4 is difficult. Using the same distributions of the maximum annual increase ratios which were tuned for the "wait and concentrate investment" decision method, the results are as shown in Figures 29-32. These graphs show the effectiveness of the wait and concentrate investment decision method for the investor to earn more profits, even the cumulative capacity of wind turbine is approximately the same amount of "classical BCA" or "combination of LBD & BCA". These graphs also show that when using these variations there is a delay in the diffusion of wind generation when the investor selects the "wait and postpone" decision method. However, as this decision method is the least profitable of the 4 decision methods, investors will not take "wait and postpone" decision method if they simulate their profit.

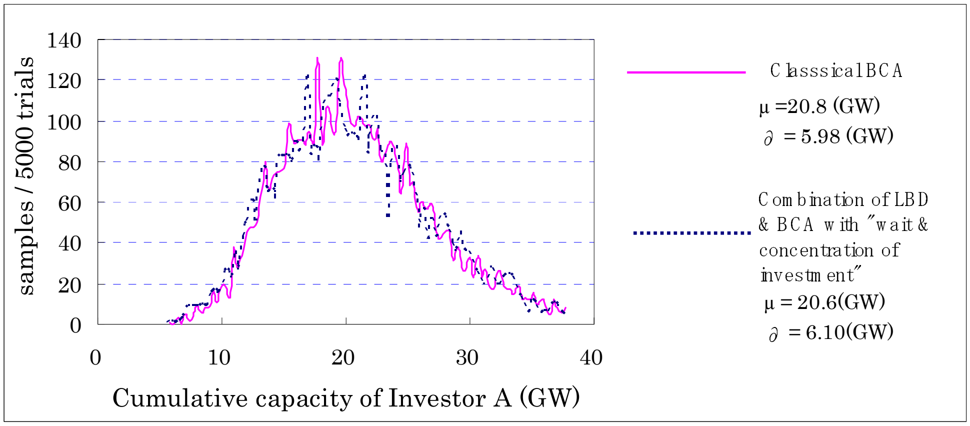


Figure 29: Simulated cumulative total capacity in 2000, simulated since 1990, based on classical BCA, and LBD and BCA with the "wait and concentrate investment method". The investment demand to supply capacity ratio is approximately 1:1. Both decision methods use the same distribution tuned for the "wait and concentrate investment method". There is no significant difference in cumulative capacity in 2000.

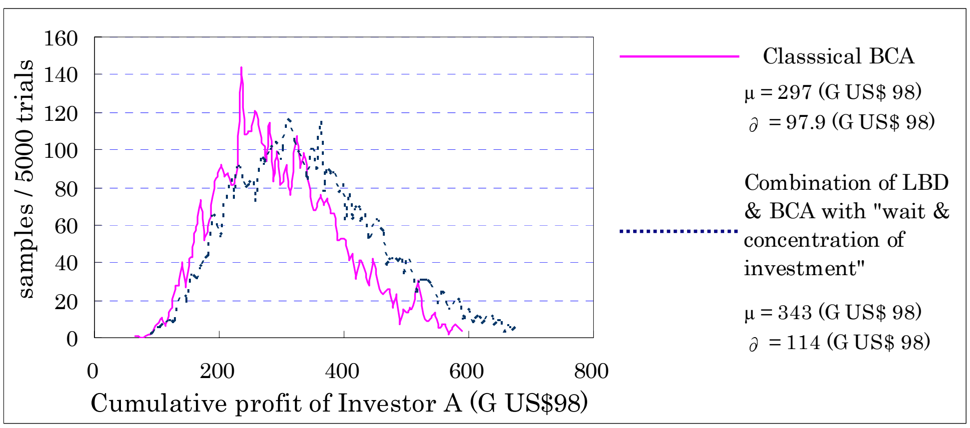


Figure 30: Simulated cumulative profits of Investor A in 2000, simulated since 1990, based on classical BCA, and LBD and BCA with the "wait and concentrate investment method". The investment demand to supply capacity ratio is approximately 1:1.

The combination of LBD and BCA with the "wait and concentrate investment method" is more profitable than the combination with classical BCA. Even the cumulative capacity of wind turbines is approximately the same.

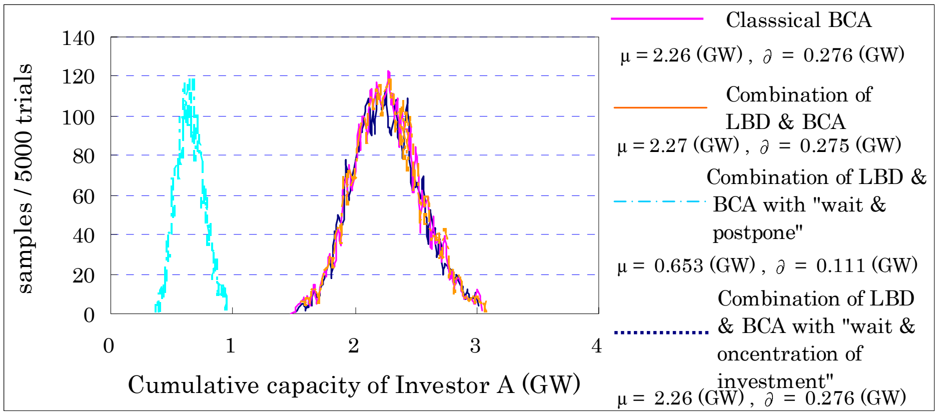


Figure 31: Simulated cumulative total capacity in 2000, simulated since 1990, based on the following four decision methods: (1) classical BCA, (2) LBD and BCA without wait, (3) LBD and BCA with “wait and postpone”, and (4) LBD and BCA with “wait and concentrate investment”. The investment demand to supply capacity ratio is approximately 1:3. Each decision method uses the same distribution tuned for “wait and concentrate investment”. There is no significant difference in cumulative capacity in year 2000 except that of “wait and postpone”. It resists wind turbine diffusion very strongly.

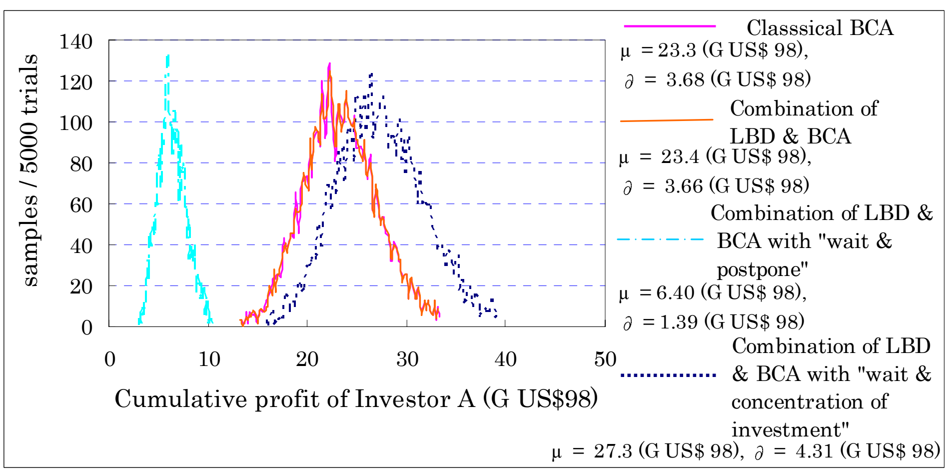


Figure 32: Simulated cumulative profits of Investor A in 2000, simulated since 1990, based on the following four decision methods: (1) classical BCA, (2) LBD and BCA without wait, (3) LBD and BCA with “wait and postpone”, and (4) LBD and BCA with “wait and concentrate investment”. The investment demand to supply capacity ratio is approximately 1:3. Each decision method uses the same distribution tuned for “wait and concentrate investment”. “Wait and concentrate investment” enables investors to earn more, while cumulative capacity nearly equals to that of “classical BCA” or “combination of LBD & BCA”.

5.3. Result of "wait and concentrate investment" decision method versus "classical BCA" decision method

Until now, this paper only discussed the situations in which both investors select the same decision method. However, what would happen when two investors select different decision methods?

In this section, we describe the case study where Investor A selects the decision method of the combination of BCA and LBD with the "wait and concentrate investment" and Investor B selects the "classical BCA" decision method. The optimization procedure is the same as in Section 5.2 (see Appendix B), however the objective function of the optimization is the sum of the cumulative profits of Investor A and Investor B. On the other hand, discount return ratio (DRR) of Investor B is changed to a fixed value of 5% in order to compare the decision method for the same time period.

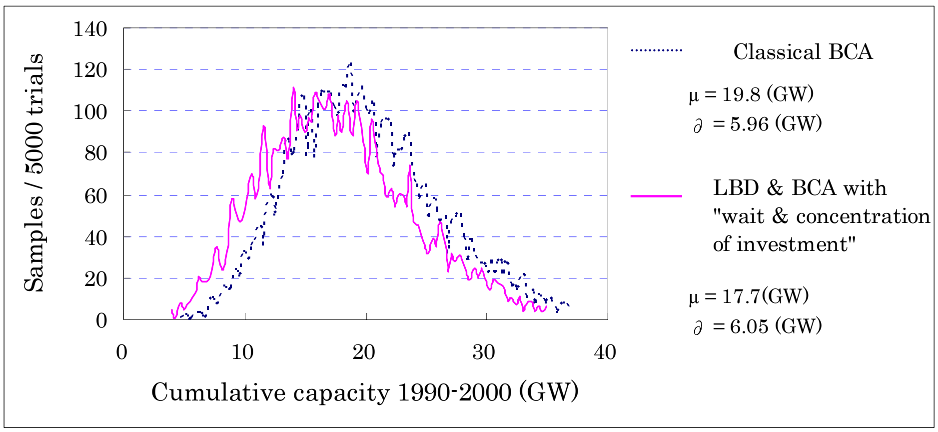


Figure 33: Probability of the cumulative capacity of investors in 2000, simulated since 1990: maximum assumed increase ratio is 1.

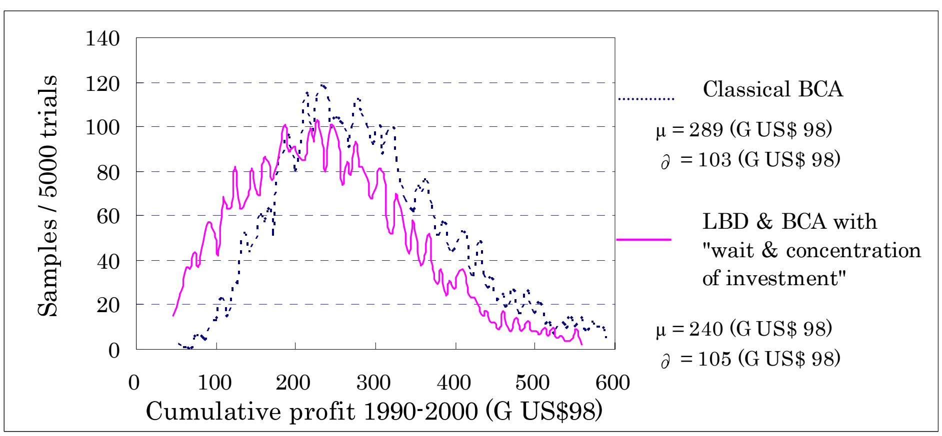


Figure 34: Probability of the cumulative profit of investors in 2000, simulated since 1990: maximum assumed increase ratio is 1.

Figures 33-34 are the results in a situation in which the maximum assumed increase ratio is 1. This assumption represents a lack of sufficient supply ability for the concentrated investment when Investor A tries to concentrate his investment in a certain year. Investor A selects the “combination of BCA and LBD” with the “wait and concentrate investment” decision method; Investor B selects the “classical BCA” decision method. The demand/supply ratio is so big that the efficiency of the “wait and concentrate investment” decision method doesn’t significantly affect this situation: The profit of Investor A is smaller than that of Investor B. Therefore, Investor A may prefer other decision methods, such as classical BCA, in which case diffusion would proceed automatically. Here however, where the assumed maximum increase ratio is limited to 1, the “wait and concentrate investment” decision method is less effective than the classical BCA decision method. To accelerate wind turbine diffusion in this situation, sufficient manufacturing supply capacity – to satisfy the full demand for the concentrated investment – should be ensured, e. g., by subsidies, taxation or some other incentives for wind turbine manufacturers. Another way to enhance wind turbine diffusion could be for Investor A to also invest in the wind turbine manufacturing capacity when he chooses the “wait and concentrate investment” method.

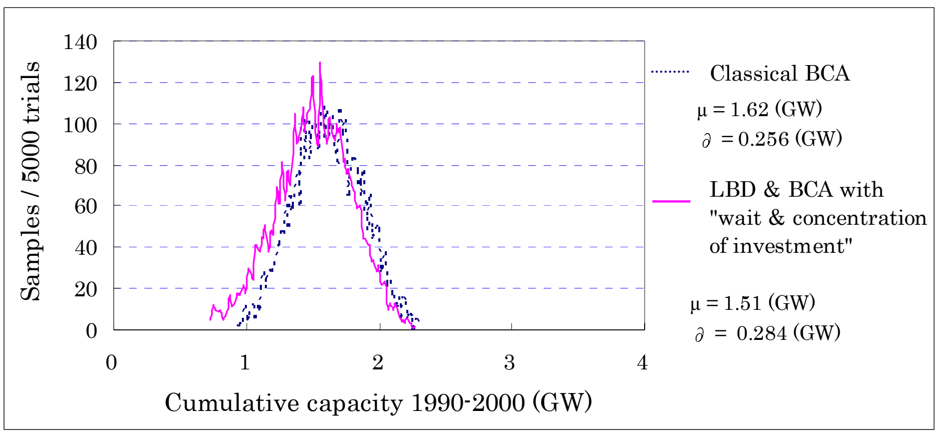


Figure 35: Probability of the cumulative capacity of investors in 2000, simulated since 1990: maximum assumed increase ratio is 1/3.

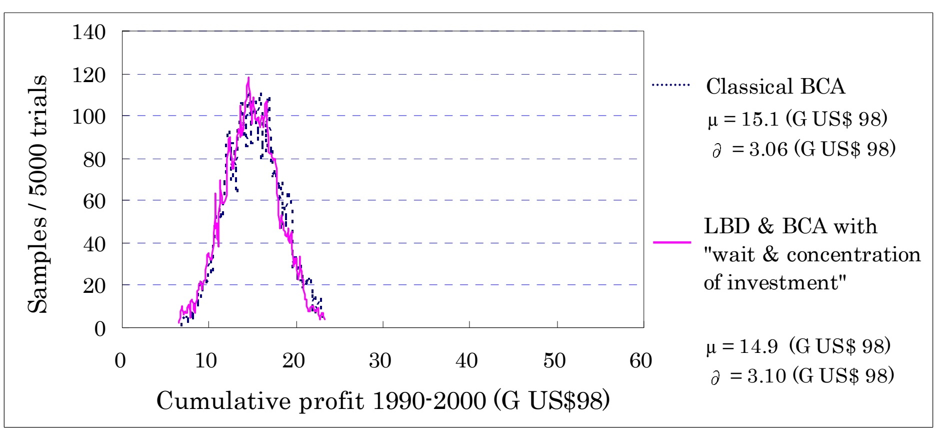


Figure 36: Probability of the cumulative profit of investors in 2000, simulated since 1990: maximum assumed increase ratio is 1/3.

Figures 35-36 are the results under a different situation, one in which the assumed maximum increase ratio is 1/3. The maximum increase ratio represents the maximum demand of investors. In other words, it measures the quality of an investment in this model. Investor A selects the "combination of BCA and LBD" with the "wait and concentrate investment" decision method; Investor B selects the "classical BCA" decision method. The demand/supply ratio is limited to a value so small that the investment by Investor A earns more effectively. The cumulative profit of Investor A is equal to that of Investor B, while the cumulative capacity of wind turbines owned by Investor A is significantly smaller than that of Investor B. Even though the increase ratio is one-third of that shown in Figures 33-34, both cumulative capacity and cumulative profits drop to about one-tenth of that of Figures 33-34.

Figures 33-36 illustrate the results of the optimized simulation. It is shown that Investor A loses against Investor B when the maximum annual increase ratio is 1. This is because the supply ability is not enough for the concentration; if the concentrated amount of investment is restricted by the supply ability, then his strategy will not work well. In this simulation, Investor A always tends to postpone his investment even he can earn if he invests in this year, when "wait and concentrate investment" shows more profit for the following year. Then, there is a high possibility that he defers his investment every year. This may make the result worse when the maximum annual increase ratio is 1.

However, if the increase ratios are assumed to be at the maximum 1/3, this means supply exceeds demand, the "wait and concentrate investment" decision method can appeal to investors because they can earn more because the concentration is effective. As the boundaries of investment are restricted to 1/3, the maximum amount of investment in a year is normally 2/3 as a result of the sum of two investors. However, if concentration is selected, the maximum amount of investment will exceed 2/3 as a result of the sum of two investors and the postponed investment in last year. In this case, Investor A can gain more than Investor B even though Investor B diffused wind turbines more than Investor A. This suggests that the keeping supply ability higher than demand peak level may prevent a bad effect of the "wait and concentrate investment" decision method, which investors may tend to postpone his investment to maximize their profit.

Figures 35 and 36 show the efficiency of the "wait and concentrate investment" decision method. While cumulative profits are nearly equal to each other, the cumulative capacity of wind turbine owned by Investor A, who selected "wait and concentrate investment" decision Method, is significantly lower than the capacity owned by Investor B, who selected the "classical BCA" decision Method (2 sample t-test supports these hypotheses on significance level: 5 %). This means that Investor A, selecting "wait and concentrate investment" decision method, can earn more *effectively* than Investor B who selected "classical BCA". This is the answer to the question why investors will select the "wait and concentrate investment" decision method in a competitive market when supply is sufficient for demands.

In a pure competitive market, it is difficult to know whether there is sufficient supply ability or not, because demands are an aggregated value of that of all competitors. This means a purely competitive market has risks to not select "wait and concentrate investment" decision method though there is a possibility to earn more effectively if sufficient supply is there. To keep stabilized demand or/and to keep higher supply ability level than demand peak level, caused by concentrated investment, may be one key to solve this situation.

A direct comparison of these two simulations means nothing because the limitations of the assumed increase ratio are different in these two simulations. Still, we can conclude from this comparison that keeping the assumed increase ratio 3 times higher results in an approximately 10 times higher profit and diffusion, independently from the decision method. In other words, the “maximum assumed increase ratio” is small enough to postpone an investment, which represents a low demand situation, where there is a risk of entering into a vicious cycle of very low diffusion of new technology.

Effective countermeasures aiming at stimulating demands may be promoting wind technology as a good investment. We must analyze this vicious cycle situation and establish the countermeasures by using subsidies, taxations, and other regulations. I believe such future studies will help the real world to avoid the same mistake not only in the wind turbines diffusion, but also all kinds of kinds of new technology diffusions, as long as LBD applies to these technologies. Based on the results, to design subsidies and taxation systems for the rapidly diffusing utility technologies such as wind turbines, we should consider the incentives not only for the investors or consumer but also for the wind turbine manufacturer to prepare sufficient manufacturing margin for the concentrated peak demand of the investors who takes “wait and concentrate investment” decision method. Otherwise, diffusion will not go well.

6. Conclusions

In this paper a combination of learning-by-doing (LBD) and benefit-cost analysis (BCA) are presented using a dynamic programming method with stochastic assumption analysis to find a way to accelerate the diffusion of wind turbine generators. In examining this combination, the “waiting option” and “postponed or concentrated” investment methods should be considered to earn more effectively for investors and to diffuse more cleaner energy effectively for all the stakeholders involving global warming, while the price comes down with the LBD concept in a competitive market.

Application of the model, which is using real data on the diffusion of wind power generation in Germany from 1990 to 2000, confirmed that the combination will affect the acceleration of diffusion of wind turbines where investors seek to optimize their investments to maximize their profit. At the same time, there still remains the uncertainty of the future which includes the vicious circle of the “waiting option” especially with the “wait and postpone” decision method with low demand in investors. Sufficient supply ability leads the investors to a “wait and concentrate investment” decision ruling market where investors can earn.

This study shows that the predictability of cost reductions according to the LBD concept does not necessarily have a beneficial effect on the diffusion of wind turbines: There is a risk of a vicious circle retarding diffusion, especially with the “wait and postpone” decision method. Without sufficient manufacturers’ ability to manufacture wind turbines, the possibility of the “wait and concentrate investment” decision method to allow investors to earn more effectively without a negative effect on the diffusion won’t appear. If there are low demands, there is always a high risk of the vicious cycle of lower diffusion, no matter which decision method investors take. Effective countermeasures aiming at stimulating demands may be promoting wind technology as a good investment. We must analyze this vicious-cycle situation and establish countermeasures, for instance by using subsidies, taxations, other regulations, and effectual investor relation (IR). This should be taken into consideration in the design of policy to encourage the diffusion of new technologies, especially a situation where supply ability is lower than demand with an instable peak demand or in a situation where low demand is based on a low reputation of the investment.

I believe that future studies in this area will help the real world to avoid such a mistake not only in the wind turbines diffusion, but also all kinds of kinds of new-technology diffusions, as long as the LBD concept applies to these technologies. Based on the results, to design subsidies and taxation systems for the rapidly diffusing utility technologies such as wind turbines, we should consider the incentives not only for the investors and consumers but also for the wind turbine manufacturers to prepare a sufficient manufacturing margin for the concentrated peak demand of the investors who select the "wait and concentrate investment" decision method. Otherwise, diffusion will not go well.

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Appendix A: Overall definition of the simulation model for combining LBD and BCA

A.1. Notation of environmental parameters

The model incorporates a number of parameters. These parameters are characterized into two groups. One group consists of the environmental parameters, and the other of the decision management parameters. In this section, the environmental parameters are described.

Y: The most significant parameter of environment is time. In this model, the time step is one year.

$Capa_{Y-1}$: Cumulative wind turbine capacity in year Y-1, known as the statistic value in year Y.

α & β : The learning curve is described based on two parameters to predict the investment from the cumulative capacity of wind turbines. The first one is the parameter of the initial value of the investment. The second one is the parameter which shows the character of the decrease. Both of these parameters are estimated as parameters which have uncertainty with a normal distribution.

α : Bias value of the initial cost. This value is assumed to have a normal distribution, with a mean value of 2853 and standard deviation of 20, based on the real statistic values for Germany.

β : Learning index. The value is assumed to have a normal distribution, with a mean value of -0.19, and standard deviation of 0.02, based on the real statistic value for Germany.

$Asm_{A1}\_Cost_Y$: Investment per kW in year *Y* assumed by Investor A.

$Asm_{B1}\_Cost_Y$: Investment per kW in year *Y* assumed by Investor B.

$Asm_{A2}\_Cost_Y$: Investment per kW in year *Y* assumed by Investor A, if Investor A postponed his investment in year *Y*.

$Asm_{B2}\_Cost_Y$: Investment per kW in year *Y* assumed by Investor B, if Investor B postponed his investment in year *Y*.

Investment per kW in year *Y* is explained in the same formula, not dependent on the investor or investors' decision to withhold the investment in year *Y*.

$$\begin{aligned} &Asm_{A1}\_Cost_Y = Asm_{B1}\_Cost_Y = Asm_{B2}\_Cost_Y = Asm_{A2}\_Cost_Y \\ &= \alpha + LN(CAPA_{Y-1})^{\beta} \end{aligned} \quad (1)$$

In this formula, there is no parameter for time. Time is introduced by the timing of investment. After introducing time, we can formulate this problem as a dynamic programming (DP) problem.

FP_y: Feed-in price of electricity generated by wind turbines in year *Y*. These values are described by a log-normal distribution. Mean values are based on the historical and present planning values. Standard deviations are assumed to be 3 (UScents98/kWh).

The parameter of the feed-in price of selling electricity to electricity distributors is the most important environmental parameter for estimating the income of the investors. The feed-in price is closely related to the price of other fuels, such as oil, coal and so on. In Germany, until March 2000, the feed-in price was regulated at 90% of the consumer tariff of electricity two years previously. (e.g. Wind Turbine's feed in price in march 2000 is 90% of 1998 consumer tariff.) If construction period is less than 1 year, the investor of wind turbine could know the feed-in price for only following one year, and the price further into the future than two years is unknown. But the electricity generated by the wind turbines should be bought by the electricity distributors; this makes the investment decision easier than where there is a risk of excess or surplus wind turbine capacity existing. In April 2000, the German feed-in price system was changed to make it much easier for investors to predict the feed-in price (EEG). Under the new system, the feed-in price is fixed in a constant price until 2005, and decreases 5% per year thereafter. This is helpful in considering the benefit of investigation and also makes the model simpler. If there were no feed-in price regulations, investors would have to consider the market balance of the feed-in price into the far future. In this model, the feed-in price is estimated based on real feed-in price changes, but still including considerable uncertainty in a log-normal distribution.

L_y: Service lifetime of wind turbines constructed in year *y*. As described using a Weibull distribution, the distribution is rounded off to a year. Rounded-off service lifetime is used to assume the possible earning years.

The parameter of the service lifetime of the wind turbine is also a major parameter. If the turbine breaks before the estimated return has been made, the investment will be lost. The probability of the service lifetime is assumed to be a Weibull distribution (position: 0 (years), scale parameter: 20, shape parameter: 20).

Efc_Y: Operational rate of year *Y*. These values are described also by a log-normal distribution. The values are based on the historical mean value of 20% and standard deviations of 3%.

Wind turbine efficiency is another important parameter. If the average wind is lower than expected, the efficiency of the generator will also be lower than expected. Wind turbine efficiency is proportional to the cube of wind velocity. Thus the result of a miscalculated prediction of the average wind velocity at the constructing place could be a big difference in the actual efficiency of the wind turbine. When there are a lot of wind turbines, however, the calculation of the wind velocity will cancel each other out, and the distribution of efficiency should be a normal distribution as a result of the law of large numbers. In this paper, therefore, the efficiency of the wind turbine is assumed to be a log-normal distribution. Generally, the efficiency of the wind turbine is expected to be 20% or more.

Drr_A: Discount return ratio of Investor A is fixed at 0.05 in each year.

Drr_B: Discount return ratio of Investor B is a log-normal distribution, with a mean value of 0.05 and standard deviation of 0.01.

These two parameters are the most important environmental parameters. The discount return ratio (DRR) of Investor A is assumed to be a fixed parameter of 5%. But the DRR of the rivals should be treated as an unknown parameter having uncertainty. Thus, the DRR of Investor B is also described by a log-normal distribution.

A.2. Notation of the decision management parameters

Each of these parameters includes uncertainty, but some can be determined by the investors.

The first parameter is the amount of the investment of Investor A. This is described as the stochastic value of the investment budget of Investor A. The second parameter is that of the competitor (Investor B). The third one is the construction capacity of wind turbine plant.

As mentioned in Section 3, a simulation of the combination of LBD and BCA requires some assumptions to be made about investors' investment strategies. This paper considers some patterns of stochastic strategies, for example, rectangular distribution and Weibull distribution. In Section 5 and Appendix B, some other distributions are considered based on the results of optimization described in section 4 and Appendix A.

$Asm_{A1}\_IncRatio_{AY}$: Increase ratio of Investor A in year *Y* to the cumulative capacity of wind turbines in year *Y-1* prior assumption by Investor A, stochastic value.

$Asm_{A1}\_IncRatio_{BY}$: Increase ratio of Investor B in year *Y* to the cumulative capacity of wind turbines in year *Y-1* prior assumption by Investor A, stochastic value.

$Asm_{B1}\_IncRatio_{AY}$: Increase ratio of Investor A in year *Y* to the cumulative capacity of wind turbines in year *Y-1* prior assumption by Investor B, stochastic value.

$Asm_{B1}\_IncRatio_{BY}$: Increase ratio of Investor B in year *Y* to the cumulative capacity of wind turbines in year *Y-1* prior assumption by Investor B, stochastic value.

$Asm_{A1}\_IncRatio_{A(Y+1)}$: Increase ratio of Investor A in year *Y+1* to the assumed cumulative capacity of wind turbines in year *Y* prior assumption by Investor A, stochastic value.

$Asm_{A1}\_IncRatio_{B(Y+1)}$: Increase ratio of Investor B in year *Y+1* to the assumed cumulative capacity of wind turbines in year *Y* prior assumption by Investor A, stochastic value.

$Asm_{B1}\_IncRatio_{A(Y+1)}$: Increase ratio of Investor A in year *Y+1* to the assumed cumulative capacity of wind turbines in year *Y* prior assumption by Investor B, stochastic value.

$Asm_{B1}\_IncRatio_{B(Y+1)}$: Increase ratio of Investor B in year *Y+1* to the assumed cumulative capacity of wind turbines in year *Y* prior assumption by Investor B, stochastic value.

$Asm_{A2}\_IncRatio_{AY}$: Increase ratio of Investor A in year *Y* to the cumulative capacity of wind turbines in year *Y-1* assumed by Investor A when the investor holds back his investment in year *Y*, stochastic value.

$Asm_{A2}\_IncRatio_{A(Y+1)}$: Increase ratio of Investor A in year *Y+1* to the cumulative capacity of wind turbines in year *Y* assumed by Investor A when the investor holds back his investment in year *Y*, stochastic value.

$CnstRatio_{Y}$: Limitation ratio of wind turbine construction capacity in year *Y* to the assumed cumulative wind turbine capacity in year *Y-1*. This parameter is also a decision management parameter, not of Investor A or B, but of the wind turbine manufacturer's plant investment.

In each case, the maximum productive wind turbine construction capacity is of major importance, so the models were simulated with several levels of productivity capacity.

In the simulation, none of the three investors (two investors A and B, and an investor for the wind turbine manufacturer) knows the amount of investment by the others. There is thus the possibility of too much or too little capacity being ordered by wind turbine generating investors from wind turbine manufacturers. To take into account some patterns of the balance of supply and demand, the following parameter was adopted.

Demand/Supply: Mean value of demand for wind turbine construction (investment in wind turbines) divided by mean value of limitation ratio of wind turbine construction capacity.

The mean increase ratios of Investor A and B are initially assumed to be of the same class (balanced). Later on in the paper, we consider the unbalanced increase ratio of investors. The investment power of Investor A to Investor B is assumed to be 1:1, 1:0.1, and 1:0.01.

A.3. Relations of parameters in functions and equations

In this section, the relations of the parameters introduced in above (Appendix A.1 and A.2) are described.

$Asm_{A1}\_AddCapa_{AY}$: Assumed additional capacity by Investor A in year *Y*, based on the prior assumption of Investor A.

$$Asm_{A1}\_AddCapa_{AY} = Asm_{A1}\_IncRatio_{AY} \cdot Capa_{Y-1} \quad (2)$$

$Asm_{A1}\_AddCapa_{BY}$: Assumed additional capacity by Investor B in year *Y*, based on the prior assumption of Investor A.

$$Asm_{A1}\_AddCapa_{BY} = Asm_{A1}\_IncRatio_{BY} \cdot Capa_{Y-1} \quad (3)$$

$Asm_{A1}\_Capa_{Y}$: Assumed cumulative capacity in year *Y*, based on the prior assumption of Investor A.

$$\begin{aligned} Asm_{A1}\_Capa_{Y} &= Capa_{Y-1} + Asm_{A1}\_AddCapa_{AY} + Asm_{A1}\_AddCapa_{BY} \\ &= (1 + Asm_{A1}\_IncRatio_{AY} + Asm_{A1}\_IncRatio_{BY}) \cdot Capa_{Y-1} \end{aligned} \quad (4)$$

$Asm_{A1}\_Bft_{A(Y)}$: Assumed cumulative benefit of Investor A from the investment in year *Y*, based on the prior assumption of Investor A.

$(Asm_{A1}\_Bft_{A(Y+1)})_{DSC}$: Assumed cumulative benefit of Investor A from the investment in year *Y+1*, based on the prior assumption of Investor A, discounted by DRR_A to adjust to year *Y*.

$(Asm_{A2}\_Bft_{A(Y+1)})_{DSC}$: Assumed cumulative benefit of Investor A from the investment in year *Y+1*, when he postponed his investment of year *Y until year Y+1,* discounted by DRR_A to adjust to year *Y*.

$Asm_{B1}\_AddCapa_{AY}$: Assumed additional capacity by Investor A in year *Y*, based on the prior assumption of Investor B.

Both investors decide their investment amount tentatively and try to order manufacturer to build their intended amount of wind turbines. However, there is a limitation of ability of manufacturer to build wind turbine in a year. When the aggregated amount of their orders exceeds manufacturer's ability, the manufacturer has to refuse exceeded order. In other words, when demands exceed supply, manufacturer and wind turbine investors have to negotiate each other. In such case, the manufacturer accepts both investors' order commensurately to each investor's order within his limitation, in this model.

Even if demands exceed supply, the price of the wind turbine will follow the LBD curve in the model.

$Tnt\_AddCapa_{AY}$: Tentatively decided additional capacity by investment of Investor A in year *Y*

$Tnt\_AddCapa_{BY}$: Tentatively decided additional capacity by investment of Investor B in year *Y*.

$Dcd\_AddCapa_{AY}$: Conclusive additional capacity of Investor A in year *Y*, negotiated with wind turbine manufacturer.

$Dcd\_AddCapa_{BY}$: Conclusive additional capacity of Investor B in year *Y*, negotiated with wind turbine manufacturer.

$$Capa_Y = Capa_{Y-1} + Dcd\_AddCapa_{AY} + Dcd\_AddCapa_{BY} \tag{5}$$

$CnstAbility_Y$: Construction ability of wind turbine manufacturer in year Y.

$$CnstAbility_Y = CnstRatio_Y \cdot Capa_{Y-1} \tag{6}$$

Using this limitation, the actual additional capacity in year *Y* is decided as below.

If

$$Tnt\_AddCapa_{AY} - Tnt\_addCapa_{BY} \geq CnstAbility_Y \tag{7}$$

Then,

$$Dcd\_AddCapa_{AY} = \frac{Tnt\_AddCapa_{AY}}{Tnt\_AddCapa_{AY} + Tnt\_AddCapa_{BY}} \times CnstAbility_Y \tag{8}$$

$$Dcd\_AddCapa_{BY} = \frac{Tnt_B\_AddCapa_{BY}}{Tnt\_AddCapa_{AY} + Tnt\_AddCapa_{BY}} \times CnstAbility_Y \tag{9}$$

Else,

$$Dcd\_AddCapa_{AY} = Tnt\_AddCapa_{AY} \tag{10}$$

$$Dcd\_AddCapa_{BY} = Tnt\_AddCapa_{BY} \tag{11}$$

A.3.1. Calculation of benefit when investment is not postponed

The electricity generated by wind turbines is calculated by multiplying the capacity of the assumed investment in year 1 or 2 (*Y* or *Y+1*) and the efficiency of the wind turbine until the expiration of the service lifetime. The estimated income string after the investment in a certain year *Y* will be calculated by multiplying the efficiency of the wind turbine generation, the feed-in price string of consecutive years, and the capacity invested in year *Y*. The net-present-value of the income string will be calculated using the discount return ratio and aggregated into one as the "benefit" of the investment in a certain year.

When Investor A doesn't consider postponing his investment in year *Y* and *Y+1*, the assumed benefits are as given below.

$$Asm_{A1}\_Bft_{AY} = Asm_{A1}\_AddCapa_{AY} \cdot Efc_Y \sum_{y=Y}^{Y+L_Y} \left(\frac{FP_y}{(1+Drr_A)^{y-Y+1}} \right) \tag{12}$$

The discounted benefit of year 2 (*Y+1*) should be discounted one more time to adjust the value in year 1 (*Y*).

$$(Asm_{A1}\_Bft_{A(Y+1)})_{Dsc} = \frac{Asm_{A1}\_AddCapa_{A(Y+1)} \cdot Efc_{Y+1} \sum_{y=(Y+1)}^{(Y+1)+L_{Y+1}} \left(\frac{FP_y}{(1+Drr_A)^{y-(Y+1)+1}} \right)}{1+Drr_A}$$

$$= \frac{Asm_{A1}\_Bft_{A(Y+1)}}{1+Drr_A} \tag{13}$$

A.3.2. Calculation of benefit when investment is postponed

When Investor A postpones his investment in year *Y*, the assumed benefits are as given below.

$Asm_{A2}\_Bft_{A(Y)}$: Assumed cumulative benefit of Investor A from the investment in year *Y*, based on assumption that Investor A will defer his investment in year *Y*.

In wait and postpone decision method, the investment amount in year *Y* when postponed is defined as below:

$$Asm_{A2}\_IncRatio_{AY} = 0 \tag{14}$$

Hence

$$Asm_{A2}\_AddCapa_{AY} = 0 \tag{15}$$

Using this equation, the assumed benefit of Investor A in year 1 (year *Y*) is described as follows:

$$\begin{aligned} Asm_{A2}\_Bft_{AY} &= Asm_{A2}\_AddCapa_{AY} \cdot Efc_Y \sum_{y=Y}^{Y+L_Y} \left(\frac{FP_y}{(1+Drr_A)^{y-Y+1}} \right) \\ &= 0 \end{aligned} \tag{16}$$

The assumptions concerning the amounts of investment in year 2 (year *Y+1*) by Investors A and B are also independent, as for year 1 (year *Y*). Investment A (or B) is considered to be one of two types. The description in this section refers to the type of investor that postpones the investment in year 1 (year *Y*), which is assumed not to be invested in year 1 (year *Y*) but in year 2 (year *Y+1*). (See middle of Fig. 9)

In this situation, if the waiting option was selected by Investor A, year 2 (year *Y+1*) investment is the same amount as the originally assumed investment in year 1 (year *Y*). This means the investment in year 1 is just deferred to the next year.

$$Asm_{A2}\_AddCapa_{A(Y+1)} = Asm_{A1}\_AddCapa_{AY} \tag{17}$$

Using this equation, the assumed benefit to Investor A in year 2 (year *Y+1*) is:

$$\begin{aligned} (Asm_{A2}\_Bft_{A(Y+1)})_{Dsc} &= Asm_{A2}\_AddCapa_{A(Y+1)} \cdot Efc_{Y+1} \sum_{y=Y+1}^{Y+1+L_{Y+1}} \left(\frac{FP_y}{(1+Drr_A)^{y-Y+2}} \right) \\ &= Asm_{A1}\_AddCapa_{AY} \cdot Efc_{Y+1} \sum_{y=Y+1}^{Y+1+L_{Y+1}} \left(\frac{FP_y}{(1+Drr_A)^{y-Y+2}} \right) \end{aligned} \tag{18}$$

A.3.3. Investment costs calculation for year 1 when investment is not postponed

Calculation of the cost is based on the simple multiplication of the investment per kW of year 1 (year *Y*) (or year 2 (year *Y+1*)) and the amount of investment in capacity in year 1 (or year 2). A feature of the combination of LBD and BCA is the estimation of the investment per kW in a year. In this paper, operation and maintenance cost are included in the initial investment.

In year 1, the investment per kW is simply estimated from the formula of the LBD curve using the cumulative amount of capacity in year 0, for which historical statistical values may be used.

$$\begin{aligned} Asm_{A1}\_Cost_Y &= Asm_{B1}\_Cost_Y = Asm_{B2}\_Cost_Y = Asm_{A2}\_Cost_Y \\ &= \alpha + LN(CAPA_{Y-1})^{\beta} \end{aligned} \tag{19}$$

$Asm_{A1}\_InvCost_Y$: Investment of Investor A in year *Y* prior assumption by Investor A.

$$Asm_{A1}\_InvCost_Y = Asm_{A1}\_AddCapa_{AY} \cdot Asm_{A1}\_Cost_Y \tag{20}$$

A.3.4. Investment calculation for year 2 when the investment is not postponed

In year 2 (year *Y+1*), the cumulative capacity of year 1 (year *Y*) is the summation of that of year 0 (year *Y-1*) and the capacity increased in year 1. The latter is caused by Investors A and B. The total investment in year 1 by the two investors is sampled from a certain distribution.

The assumptions of the investment amount should be different from each other, so that Investor A uses the envisaged investment by himself and the assumed investment by Investor B, while at the same time Investor B uses the envisaged investment by himself and the assumed investment by Investor A. These envisaged and assumed investments are sampled from stochastic distributions independently of each other.

$$(Asm_{A1}\_Cost_{A(Y+1)})_{Dsc} = \frac{\alpha + LN(Asm_{A1}\_CAPA_Y)^{\beta}}{1 + Drr_A} \tag{21}$$

$Asm_{A1}\_InvCost_{(Y+1)}$: Investment of Investor A in year *Y+1* prior assumption by Investor A.

$$Asm_{A1}\_InvCost_{(Y+1)} = Asm_{A1}\_AddCapa_{A(Y+1)} \cdot (Asm_{A1}\_Cost_{A(Y+1)})_{Dsc} \tag{22}$$

A.3.5. Investment calculation for year 2 when the investment is postponed

In this case, the capacity increase in year 1 (year *Y*) is caused only by Investor B. (This means that, in assuming waiting, the rival always assumed to keep investing.)

The investment per kW is calculated by summing the cumulative capacity in year 0 and envisaged capacity increase in year 1 caused by Investor B.

$Asm_{A2}\_InvCost_Y$: Investment of Investor A in year Y when Investor A postponed his investment in year *Y*.

In this assumption, even if Investor A delays his investment, Investor A assumed that Investor B continues to invest. The amount of the investment by Investor B is therefore the same as for the postponed assumption. (Note that if Investor B also makes the same assumption, there is a possibility of both deciding to postpone their investment.).

$$Asm_{A2}\_AddCapa_{BY} = Asm_{A1}\_AddCapa_{BY} \tag{23}$$

$Asm_{A2}\_Capa_Y$: Assumed cumulative capacity in year *Y*, based on an assumption made by Investor A when Investor A defers his investment in year *Y*.

As mentioned in equation (14), the investment in year *Y* is postponed to the next year.

$$Asm_{A2}\_AddCapa_{AY} = 0 \tag{24}$$

Thus, the cumulative capacity of wind power in year *Y* if postponed by Investor A is assumed as below.

$$\begin{aligned} Asm_{A2}\_Capa_Y &= Capa_{Y-1} - Asm_{A2}\_AddCapa_{AY} + Asm_{A2}\_AddCapa_{BY} \\ &= Capa_{Y-1} + Asm_{A1}\_AddCapa_{BY} \end{aligned} \tag{25}$$

Using this equation, investment per (kW) in year *Y+1* is assumed.

$$Asm_{A2}\_Cost_{Y} = \alpha + LN(Asm_{A2}\_CAPA_{Y})^{\beta} \qquad (26)$$

$Asm_{A2}\_InvCost_{(Y+1)}$: Investment of Investor A in year *Y+1* when Investor A waits with his investment in year *Y*.

$$Asm_{A2}\_InvCost_{(Y+1)} = Asm_{A2}\_AddCapa_{A(Y+1)} \cdot Asm_{A2}\_Cost_{Y} \qquad (27)$$

A.3.6. Decision methods

In a pure competitive market, both Investor A and Investor B decides using only his own assumptions of future benefit and cost based on the reduced price of the wind turbines which will be changed with the aggregated investment by Investors A and B. The counterpart investment amount is assumed by one Investor, independent from the real plan of the other Investor.

With the classical BCA decision method, as the cost reduction according to the increase of the cumulative amount of the wind turbines is ignored, the decision is made as follows.

If

$$Asm_{A1}\_Bft_{AY} - Asm_{A1}\_InvCost_{AY} \geq 0 \qquad (28)$$

Then

$$Tnt\_IncCapa_{AY} = Asm_{A1}\_IncCapa_{AY} \qquad (29)$$

Else

$$Tnt\_IncCapa_{AY} = 0 \qquad (30)$$

When BCA and LBD are combined, as the cost reduction is taken into consideration, the investment decision is made as follows.

If

$$\{Asm_{A1}\_Bft_{AY} + (Asm_{A1}\_Bft_{A(Y+1)})_{Dsc}\} - \{Asm_{A1}\_InvCost_{AY} + (Asm_{A1}\_Bft_{A(Y+1)})_{Dsc}\} \geq 0 \qquad (31)$$

Or, $Asm_{A1}\_Bft_{AY} - Asm_{A1}\_InvCost_{AY} \geq 0$ (32)

Then

$$Tnt\_AddCapa_{AY} = Asm_{A1}\_AddCapa_{AY} \qquad (33)$$

Else

$$Tnt\_AddCapa_{AY} = 0 \qquad (34)$$

If BCA and LBD are combined with the waiting option, the investment decision is made as follows.

If

$$\{\{Asm_{A2}\_Bft_{AY} + (Asm_{A2}\_Bft_{A(Y+1)})_{Dsc}\} - \{Asm_{A2}\_InvCost_{AY} + (Asm_{A2}\_Bft_{A(Y+1)})_{Dsc}\}\}$$
$$-\{\{Asm_{A1}\_Bft_{AY} + (Asm_{A1}\_Bft_{A(Y+1)})_{Dsc}\} - \{Asm_{A1}\_InvCost_{AY} + (Asm_{A1}\_Bft_{A(Y+1)})_{Dsc}\}\}$$
$$\geq 0 \tag{35}$$

Then

$$Tnt\_AddCapa_{AY} = Asm_{A2}\_AddCapa_{AY} = 0 \tag{36}$$

Else If

$$\{Asm_{A1}\_Bft_{AY} + (Asm_{A1}\_Bft_{A(Y+1)})_{Dsc}\} - \{Asm_{A1}\_InvCost_{AY} + (Asm_{A1}\_Bft_{A(Y+1)})_{Dsc}\}$$
$$\geq 0 \tag{37}$$

Or, $Asm_{A1}\_Bft_{AY}$ - $Asm_{A1}\_InvCost_{AY} \geq 0$ (38)

Then

$$Tnt\_AddCapa_{AY} = Asm_{A1}\_AddCapa_{AY} \tag{39}$$

Else

$$Tnt\_AddCapa_{AY} = 0 \tag{40}$$

The same decision will be made by Investor B independently. Sometimes, therefore, both investors will decide to postpone their investments in the same year.

The probability of the decision depends on the distribution of the amount of the investment budget.

Appendix B: Definition of the simulation model for the "wait and concentrate investment" decision method

B.1. Notation and equations

Almost all notations are the same as in the Appendix A, however with the addition of six more parameters.

In Section 5, the maximum amount of the investment in the year 2 when the investor decides his investment in the next year is assumed to be the aggregation of the year 1 and the year 2's investment multiplied by the "concentration ratio" (see bottom of Figure 12). Investor may concentrate his postponed investment addition to the prior assumed investment in year 2, or may just postpone his investment for year 1 until year 2.

$Cncnt_{A(Y+1)}$ and $Cncnt_{B(Y+1)}$: The concentration ratios of investment in year 2 (year *Y+1*) of Investors A and B, stochastic value. These two parameters are the decision management parameters of investors. In this paper, these parameters are independent of each other, and the lower limit is 0 and upper limit is 1.

$Cncnt_{AY\_Y}$ & $Cncnt_{BY\_Y}$: The concentration ratios of investment in year 1 (year *Y*) when investor withholds his investment in year 0 (year *Y-1*). These two parameters are the decision management parameters of investors. Investors can change their mind after seeing competitor's investments in year 0 (year *Y-1*). In this paper, these parameters are independent of each other, and the lower limit is 0 and upper limit is 1.

$Asm_B\_Cncnt_{AY\_Y}$ & $Asm_A\_Cncnt_{BY\_Y}$: The assumed concentration ratios of investment in year 1 (year *Y*) for the assumption of the other investor's concentration in year 1 when other investors postponed their investment in year 0 (year *Y-1*).

Using these parameters, the investments in year *Y+1* are described as:

$$Asm_{A2}\_IncCapa_{A(Y+1)} = Asm_{A1}\_IncCapa_{AY} + Cncnt_{A(Y+1)} \cdot Asm_{A1}\_IncCapa_{A(Y+1)} \quad (41)$$

$$Asm_{B2}\_IncCapa_{B(Y+1)} = Asm_{B1}\_IncCapa_{BY} + Cncnt_{B(Y+1)} \cdot Asm_{B1}\_IncCapa_{B(Y+1)} \quad (42)$$

When the investor considers deferring his investment from year 1 until the following year, the investment in year 2 is assumed to equal the investment originally planned for year 1 plus the value of the concentration ratio multiplied by the investment prior planned for year 2.

When Investor A defers the investment in year *Y-1*, the prior assumed amount of investment by Investor A in year *Y* is assumed to be as follows.

$$Asm_{A1}\_IncCapa_{AY} = Asm_{A1}\_IncCapa_{A(Y-1)} + Cncnt_{AY\_Y} \cdot Asm_{A1}\_IncCapa_{AY} \quad (43)$$

$$Asm_{B1}\_IncCapa_{BY} = Asm_{B1}\_IncCapa_{B(Y-1)} + Cncnt_{BY\_Y} \cdot Asm_{B1}\_IncCapa_{BY} \quad (44)$$

This means that the added amount of the investment in year 1 and 2 (which is multiplied with the concentration ratio) will be also used only when the new incremented in "year

1” (*Y*), next to the old “year 1” (*Y-1*) in which the investor postponed his investment, as the amount of the investment of the new incremented “year 1 (*Y*)”.

Investor A can know in year *Y* that Investor B postponed his investment in year *Y-1*. So, Investor A assumes that the investment of Investor B will be concentrated in year *Y* as follows.

$$Asm_{B1}\_IncCapa_{AY} = Asm_{B1}\_IncCapa_{A(Y-1)} + Asm_{B}\_Cncnt_{AY\_Y} \cdot Asm_{B1}\_IncCapa_{AY}$$
$$Asm_{A1}\_IncCapa_{BY} = Asm_{A1}\_IncCapa_{B(Y-1)} + Asm_{A}\_Cncnt_{BY\_Y} \cdot Asm_{A1}\_IncCapa_{BY}$$

In this paper, as the functions are written above, the postponed amount of investment in year *Y-1* is available only in year *Y*, but not in year *Y+1* or later.

Other notations, equations and decision methods are completely the same as those described in Section 4.

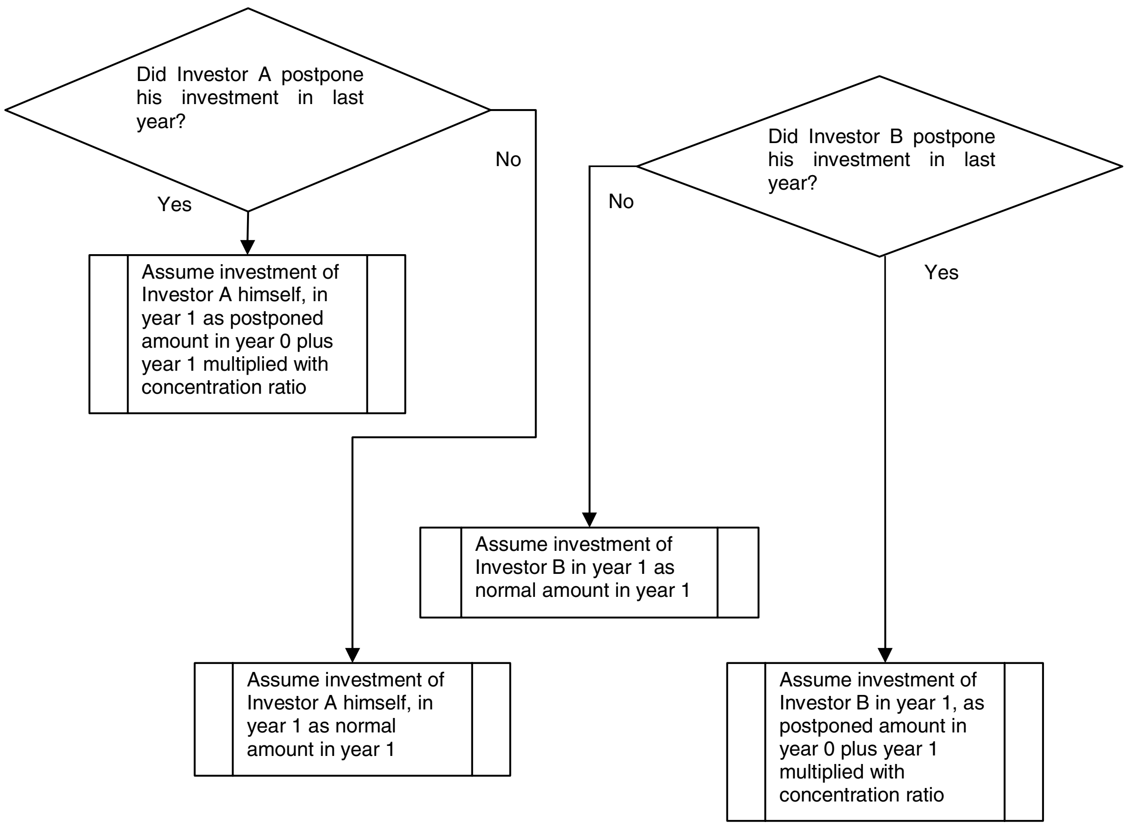

Figure 37: Assumption of the concentrate amount of investments in year 1 (year *Y*) when postponed in year 0 (year *Y-1*).

In year *Y*, Investor A may know that Investor B postponed his investment in year *Y-1*. Investor A can assume the concentration ratio of Investor B in year *Y*.

B.2. Optimization procedure for the "wait and concentrate investment" method

To maximize their cumulative profit in this situation, in this paper, Berman's backward optimization method of dynamic programming (DP) is not applied. This does not directly mean that this problem is an exceptional item of dynamic programming. As in a competitive market there are other independent actors also capable of making decisions about the future, however, solving with backward DP is not easy. The following procedure was therefore applied in this paper to deal with this problem (Glover, *et al*., 1996;, 1997; Laguna, 1999; Kall, *et al*., 1994; Infanger, 1994; Trick, 1998).

The decision parameters of both Investors are defined under several limiting conditions. The decision parameters of one Investor are assumed to be stochastic parameters following a rectangular distribution and with the same limiting condition as the other Investor's decision parameters. Stochastic parameters are re-sampled in each iteration. Even though these stochastic parameters are arranged in order of time, the re-sampling process takes place at the beginning of each iteration. Using the Latin-hyper-cube sampling method, the possibility (i.e., uncertainty) is calculated for some combinations of these parameters. After these calculations, metaheuristic optimization (such as genetic algorithm, annealing procedure, and taboo search) is applied, and the loop of sampling, calculation, and optimization iterated (F. Glover, J.P Kelly, and M. Laguna, 1996, 1997, 1999. Kall, P and S.W. Wallace, 1994. Infanger, G. 1994).

After the first optimization, the optimized parameters for Investor A are applied to Investor B with uncertainties, and optimize again as the second step.

After the second-step optimization, the optimized parameter is changed as a result of the probability of investment of Investor B being changed from the first step.

The results of optimization are ordered according to the objective value and the optimizing datum which are near to the most optimized data, and are analyzed with distribution fitting and Spearman rank-order correlation. In this study, objective value is the present value of investor A's cash flow. After the second step, the optimized parameter of the second step is applied to Investor B again with the distribution and rank correlation of the optimization results. Using these "optimized parameters", the distribution of the decision management parameters is defined.

After the definitions of the distribution of the decision management parameters, the probability analysis is initiated and compared with other decision methods, such as the classical BCA, basic combination of LBD and BCA, and LBD and BCA with simple "wait and postpone".

In this paper, the simulation was conducted using the following parameters. The maximum annual increase ratio of the cumulative amount of wind turbines is 1. As the average demand changes year after year, the demand / supply ratio is not obvious. However the upper limit of the demand / supply ratio is restricted to certain value in this simulation. To analyze the effect of the upper limit, the results of the simulations, when upper limit are 1 and 1/3, are listed in section 5.

This optimization tool gives an "optimized result" for decision management parameters using so-called metaheuristic optimization. However, if the "optimized result" is not mathematically solved, then the result does not converge.

The “optimization” used in this paper doesn’t promise a mathematically converging result, but shows a result for practical investment decision making for.

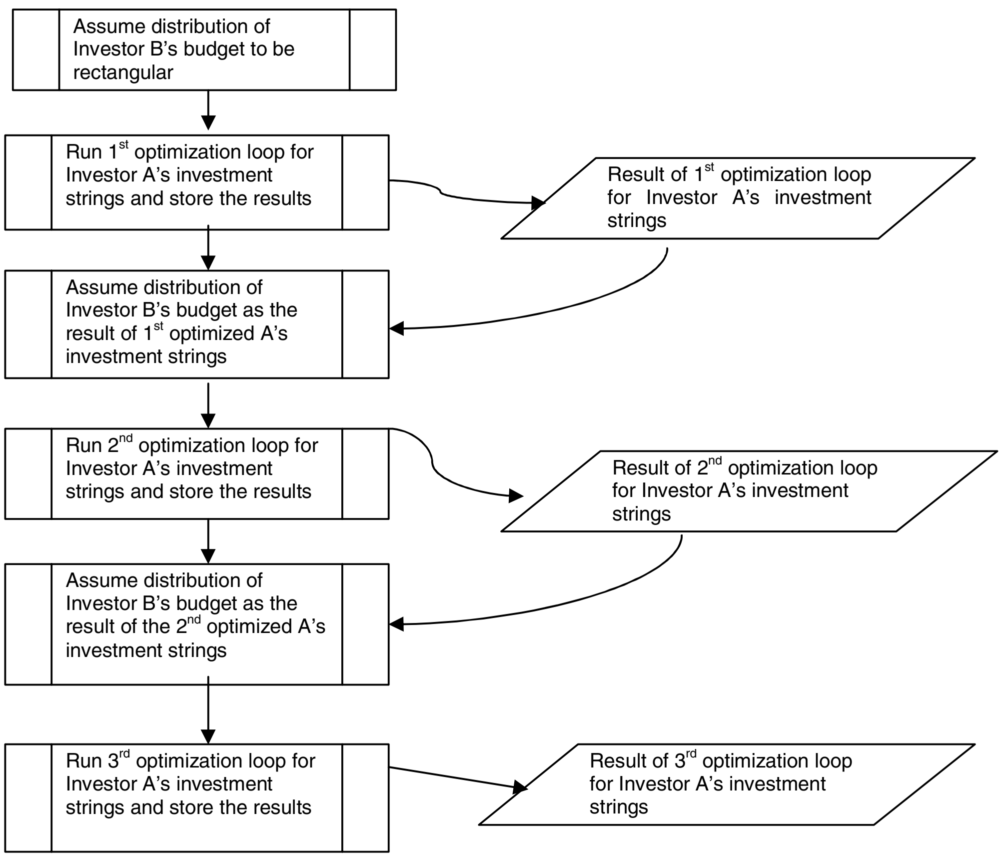

Figure 38: Usage of the “optimizations” in “wait and concentrate investment” decision method.

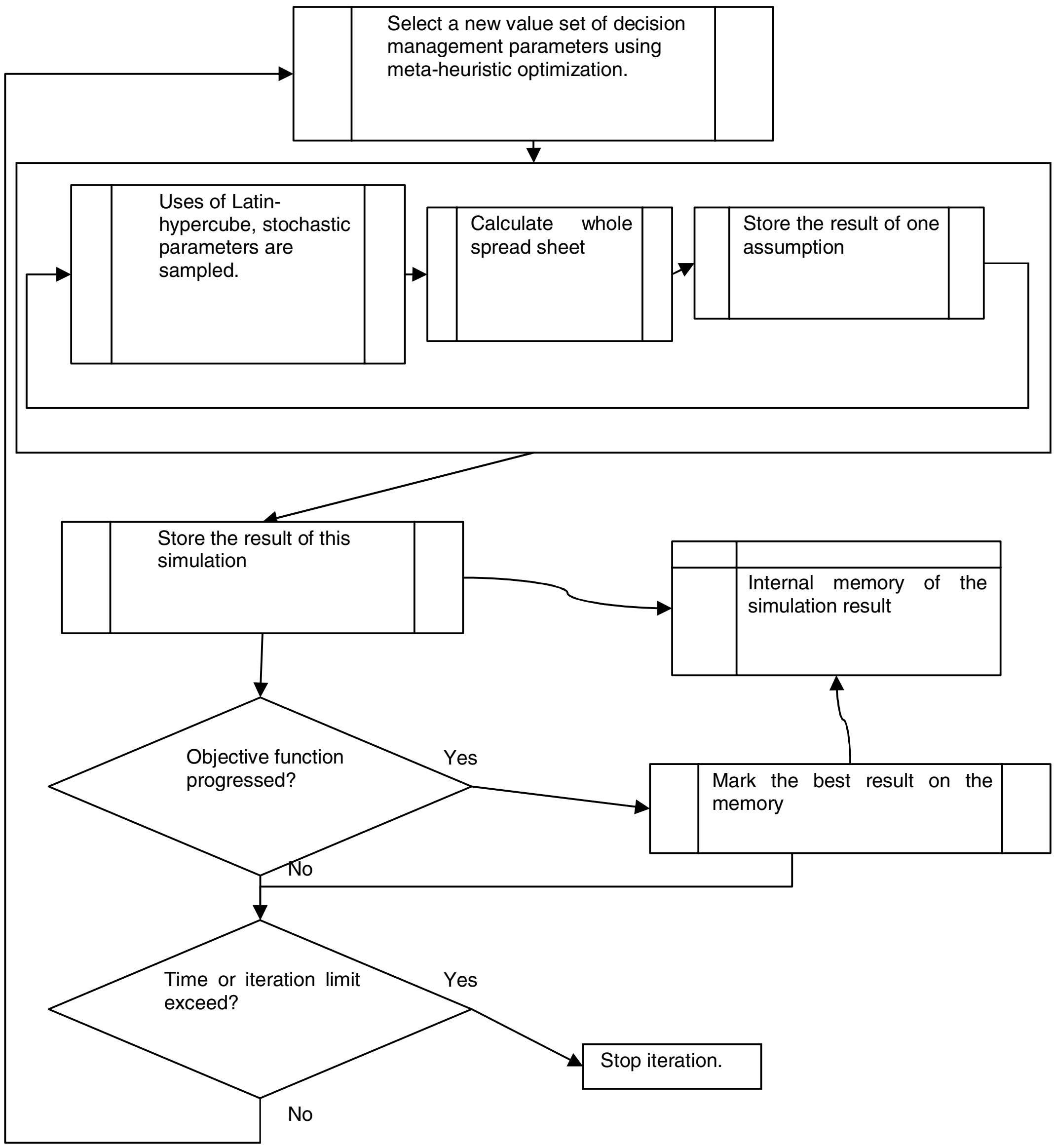

Figure 39: Basic loop of the optimization of OPT-Quest (Trade Mark).