碩士學位論文

A Comparative Study on Various Measure-Correlate-Predict Techniques in Jeju Island

濟州大學校 大學院

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A Comparative Study on Various Measure-Correlate-Predict Techniques in Jeju Island

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Feb, 2010

Gyeongil, Kwak

Abstract

A Comparative Study on Various Measure-Correlate-Predict Techniques in Jeju Island

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GYEONGIL, KWAK, MEng, JEJU NATIONAL UNIVERSITY
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For wind farm development the wind condition for the measurement period of one year is often considered. However in view of the turbine life cycle it is more important to consider the long-term wind conditions rather than those of one year or less. The Measure-Correlate-Predict (MCP) technique is a statistical method to predict the long-term wind resource at a target site, where the onsite short-term data are available, with a reference long-term data usually measured at meteorological observatories. Many MCP methods have been proposed and applied in different cases in accordance with the terrain types, data measurement period, etc, but there are still no fixed rules to apply these methods.

This study has been conducted to find a better MCP method that is in particular suitable for Jeju island which has a different terrain shapes strongly characterized by the Halla mountain centered on the island.

The three different methods such as linear regression, matrix, joint probabilistic methods were selected to compare their performance in different terrain types. The Hangwon site nearby coastal area was chosen as simple terrain type, and the Hoichun and Susan sites were selected as the mountainous-complex terrain types.

These methods have been applied in two different ways. First the linear regression method was applied to check the usefulness of it. Secondly, on the basis of the first test results, two other methods including the linear regression method were applied to each terrain type. The predicted results were compared with measured wind data including weibull parameters. The results showed the advantages of each MCP model for prediction of long-term wind conditions at target sites. It also demonstrated the limitation of these models for the different terrain types. It was shown that matrix and joint probabilistic methods were more useful in mountainous terrain than linear regression method because these methods are considering wind direction.

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NOMENCLATURE

KMA	Korean Meteorological Administration
AWS	Automatic Weather System
ASOS	Automated Surface Observing System
NCEP	National Center for Environmental Prediction
NCAR	National Center for Atmospheric Research
MCP	Measure-Correlate-Predict
WAsP	Wind Atlas Analysis and Application Program
SRTM	Shuttle Radar Topographic Mission

1. Introduction

1.1 Background

More than 80% of world energy is powered by fossil fuels and Skyrocketing oil prices have damaged the economy of the nations like Korea, which fully relies on imports for its oil suppliers. Further fossil fuels such as oil, coal, natural gas are running out and due to the desire to increase self-sufficiency energy of nations many countries are devoting the efforts to find new, clean and eco-friendly energy sources like wind, solar, etc. Among them, wind is considered the most powerful and most profitable renewable energy resource as of today, though wind is invisible and unpredictable. It is because wind power is clean, indigenous, fast to deploy and also creates many jobs.

According to Renewables Global Status Report 2009 Update [1], wind power capacity increased 250 percent to 120GW in the four years from end of the 2004 to end of the 2008. Korean Government is trying to play a leading role in this field by setting the wind energy is one of the core part to be developed in advance by 2012. After Hangwon wind farm was installed many sites which have a good wind conditions like Gangwon province have been developed and the total installation capacity in Korea has reached 317MW as of March, 2009 [2].

Following the Korean government's strategy, Jeju Special Self-governing Province, which already is operating five installed wind farms, also released a roadmap to supply 500MW of wind power facilities by 2020 including offshore wind farms for renewable energy development [3].

Wind farms can provide safe, clean and affordable power but Wind energy developments are subject to financial risk. It is a consequence of the uncertainties in the resource assessment which later will be amplified in the energy prediction due to the non linear connection between wind turbine production and wind speed. In order to avoid financial disadvantages in a wind farm development, the uncertainties must be minimized.

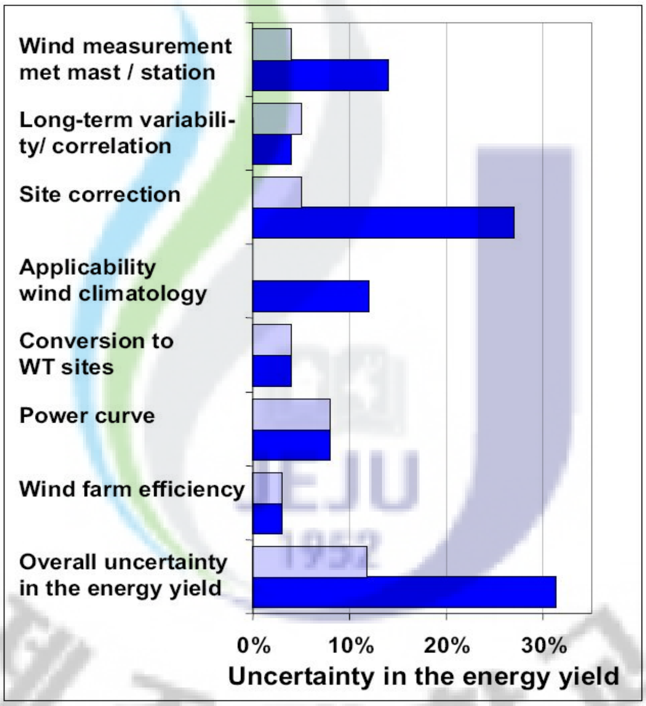

Figure 1.1. Uncertainty in the energy yield when assessment is based on a high quality wind measurement(light) and on the data from a meteorological station(dark) (Source: DEWI)

Figure 1.1 shows the overall uncertainty of an energy yield for typical situations. In this Figure, the long-term correlation is one of the driving contributions of uncertainty in the wind resource assessment process [4].

It is very important to take wind variations at longer time scales into account since one of the main goals of site assessment is to estimate the long-term wind resource. Measure-Correlate-Predict is a statistical method to predict long-term wind resource (wind speed and wind direction) at target sites for wind power development with short-term measured data.

MCP methods model the relationship between wind data (speed and direction) measured at the target site and concurrent data at a nearby reference site, over a period of up to one or two years, which is the upper limit measuring period the project is usually allowing because of financial viability. The model is then used with long-term data from the reference site to estimate the long-term wind speed and direction distributions at the target site. Using MCP method, long-term mean wind speed and wind speed distributions at the target site are obtained. Figure 2.1 shows the general MCP process.

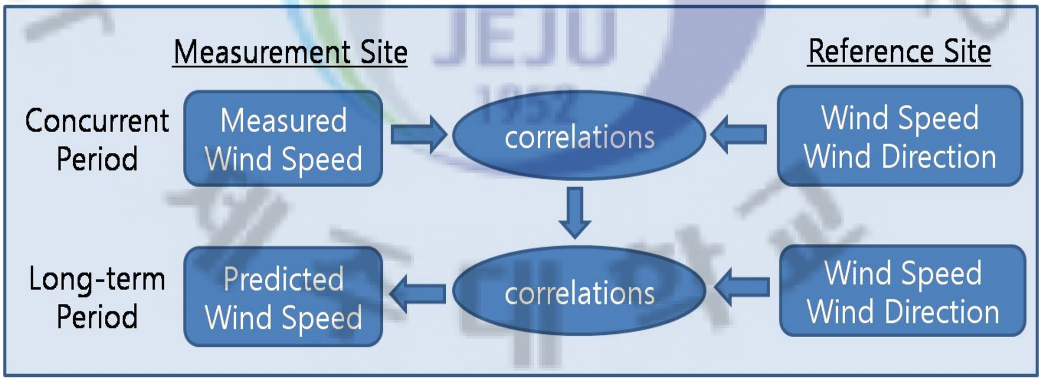

Figure 1.2 MCP Method process

The general methodology of the MCP process proceeds as follows [5].

1. Collect wind data at the predictor site for an extended period

2. Identify a reference site, for which high quality, long term records exist, in the vicinity of the target site, and which has a similar exposure.
3. Obtain wind data from the reference site for the same time period as for the target site.
4. Establish a relationship between the data from the reference and target sites for the concurrent period.
5. Obtain wind data from the reference site for a historic period of 10 to 20 years duration.
6. Apply the relationship determined from 4 above to the historic data from the reference site to 'predict' what the winds would have been at the target site over that period.

Many researchers have proposed various MCP techniques and suggested a variety of formulas to relate between wind speed and wind direction at the target and the reference sites.

The types of models include linear model [6],[7],[8], binned ratio method [9], non-linear models (DEWI) [10], matrix method [11], joint probabilistic model [12], model that used temperature (RISO) [13], variance method [14], artificial neural networks [15],[16], Markov chain model [17], Weibull model [18], FFT(Fast Fourier Transform) model [19], Kriging Method [20].

Rogers et al. [14] and Anderson et al. [5],[21] provide detailed reviews of a variety of MCP methods as well as a comparison of the performance of several methods.

1.2 Objectives

As mentioned before, Jeju island is the best place in Korea to construct a wind farm, which has a strong wind energy potential graded 3~4(fair, good) on the eastern and western coasts, and grade 5 or above (excellent) on the sea surrounding around the island[1]. Due to small mountains named Orem, a wind flow distortion is happening in Jeju island when wind is blowing.

In this study, as one of the factors which affect uncertainties in energy yield, MCP methods was applied under coastal and mountainous area. From the many suggested MCP models the questions still remains which MCP models are the better for complex terrain. Therefore to find out the more suitable MCP method for Jeju island, which has a attribute of mountainous-complex terrain, the three methods such as linear regression, matrix and joint probabilistic methods have been selected and compared in different terrains.

First a linear regression method which is most commonly used, is applied to both coastal and inland areas to check the usefulness. Secondly three types of MCP methods is selected, including the linear regression method for comparison, and those methods were applied to specific sites with the aim to find a better method for estimating wind resource using short-term measured data from Automatic Weather System (AWS) in both simple and mountainous-complex terrain [22],[23]. These three different MCP methods would be compared to show predictive accuracy of mean wind speed, wind direction and Weibull parameters.

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[1] The grades is assessed based on the annual mean wind speed and wind power density, ("Wind Resource Assessment Handbook", April 1997, NREL)

2. A Review of MCP Techniques

2.1 Linear regression method

Linear regression method is to characterize the relationship between the target site and the reference site linearly. There are some types of this method such as using the ratio of means(single and multiple sector), least squares and orthogonal regression but in this study, linear regression using multiple sector(exactly straight line with offset) was considered based on 12 sectors with each 30° bins to establish a relationship between wind speed and direction at the reference site and the wind speed at the potential wind farm site. This is expressed by

$$V_{mast} = a(V_{ref}, D_{ref})V_{ref} + b(V_{ref}, D_{ref}) \qquad 1)$$

where, V is a wind speed, D is a wind direction, subscript $mast$ and ref means target site and reference site, respectively.

The individual steps are described below:

1. Divide the concurrent data into direction bins, for example 12 bins of 30° each, based on the wind direction measured at the reference site
2. Within each sector(30° bin) linear regression is carried out to establish the correlation between wind speeds at reference and target site

In this method, it is assumed that the wind direction at the target site is the same as that at the reference site.

2.2 Matrix method

Matrix method is a technique that aims to produce better estimates of the wind direction distribution at the target site compared to the linear MCP approaches, because linear MCP method does not allow any prediction of wind direction [11],[24].

The concurrent data are used to obtain a joint frequency analysis of wind direction at the reference site and wind direction at the target site. In this study sectors are divided into 30° bins and a 12×12 matrix of frequency counts is obtained.

These counts are converted into percentage frequencies by discarding around 5% of lowest frequencies ratio because of their very little contribution to the total population of each sector. Then the jointed frequency matrix is combined with the observed counts from the long-term data at the reference site to produce estimates of the long-term wind direction distribution at the target site.

Linear regression is then used to relate the wind speeds at the two sites with a separate equation for each direction sector. The observed mean wind speed for each sector at the reference site is used with its relevant equation to produce a predicted mean wind speed for the target site. The mean wind speed for each sector at the target site is estimated by taking a weighted sum of these separate predictions to determine the weights.

2.3 Joint probabilistic method

This method is to use the joint probability of the occurrence of wind at the reference site and at the target site based on probability of occurrence of concurrent time series data. The application of the joint probabilistic theory2) to the data is as follows [12]:

1. Make a concurrent time series data of measurements at the target and the reference site.
2. Conforming a set of events in time $\lfloor V_{mast}, D_{mast_{t_i}} \rfloor_{V_{ref}, D_{ref}}$ and the same procedure is repeated for every class of event at the reference site, then make a joint probability mass function $F(V_{ref}, D_{ref}; V_{mast}, D_{mast})$
3. Once this joint probability mass function F is made, the probability distribution at the target site $P^{LT}_{mast}(V_{mast}, D_{mast})$ is obtained by applying it to the probability distribution at the reference site $P^{LT}_{ref}(V_{ref}, D_{ref})$:

$$P^{LT}_{mast}(V, D) = \sum_i \sum_j F(i, j; V, D) P^{LT}_{ref}(i, j) \qquad 2)$$

where, superscript LT means long-term, subscript $mast$ and ref

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2) 강금식, 정우석, 「Excel 활용 현대통계학(제3판)」,(서울: 박영사, 2008), p. 130~133
박범조, 「Excel을 이용한 현대통계학 이론과 활용(개정판)」(서울 : 시그마프레스(주), 2007), p. 85~100

means target and reference sites, i and j means wind speed and wind direction of reference site, respectively.

In this study wind speed bins of target and reference sites were divided 50 in intervals ranging from 0m/s to 50m/s and each wind direction of each was divided in 12 sectors with 30 degree to more easily compare with the other methods. The details of Joint probability distribution can be found in Appendix A~C with comparison to the linear regression method distribution.

3. Site Description and Data Sets

3.1 Site Description

3.1.1 Overview of Jeju island

Jeju is the only special autonomous province of South Korea, situated on the country's largest island, which lies in the Korea Strait. Jeju island is a volcanic island, which covers 1,847,000 square kilometers of land and is located at latitude 33°06' ~ 34°00' north and longitude 126°08' ~ 126°'58' east, dominated by Halla-san(Halla Mountain) which is 1,950m high. The east and west sides of Halla mountain have a gentle slope of 3°~5° inclination and the north and the south sides of the mountain show steeper slopes with 5°~10° inclination. With regards to elevation the costal area below 200m above sea level accounts for 55.3% of total Jeju area, and the area above 500m accounts for 16.8% and the intermediate area does for 27.9%.

Many small mountains in Jeju are called Orem, derived from Jeju dialect, which means small mountain. Its height ranges from 100m to 400m with the average height about 200m~300m. According to the distribution of altitude, among the total count of 368 Orem, 143 are situated in the lower coastal areas at below 200m elevation. 149 are situated in between 200m and 600m, and others are inside the Halla-san national park.

These 368 Orems, which are scattered widely on the island have the significantly different climatic zone according to the regional location and altitude.

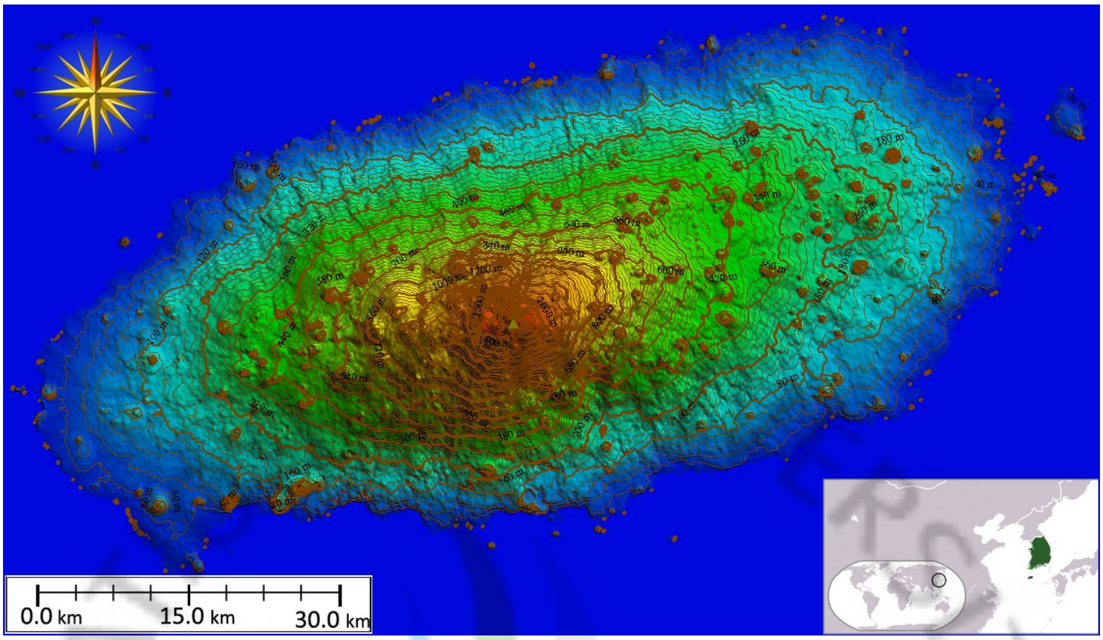

Figure 3.1 Digital topographic map of Jeju island

Figure 3.1 shows the characteristics of Jeju terrain which has many Orems. Contour lines with vertical resolution of 20m derived from the SRTM(Ver. 3) database were applied in the Figure.

3.1.2 Characteristics of each site

3.1.2.1 Hangwon site

Hangwon is located in the north-eastern part of Jeju island near the sea. As can be seen in Figure 3.2 and 3.3, which is derived from SRTM(Ver. 3) database, the terrain feature has gentle slope and no effect was observed from the terrain observation. Consequently the site can be classified as flat(simple) terrain. Figure 3.4 shows that the met. mast was erected in the vicinity of the sea. Hangwon agricultural and industry complex, massive fish farms and a village is located in the south-western direction from the mast, at distances of 500m, 800m, 1.2km, respectively. Following the coastal line small bushes and towards inland from mast windbreak forest with a canopy height of around 10m are growing.

Figure 3.2 Location of measurement site in Hangwon

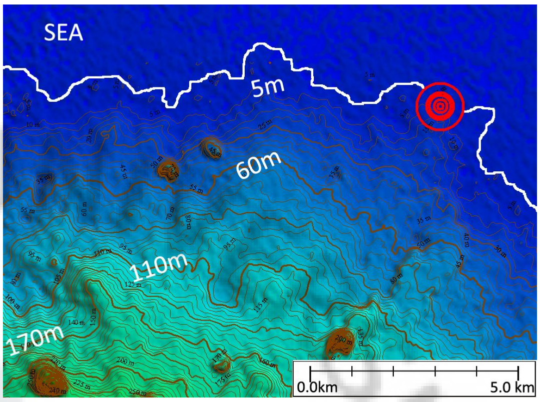

Figure 3.3 Digital terrain model of Hangwon

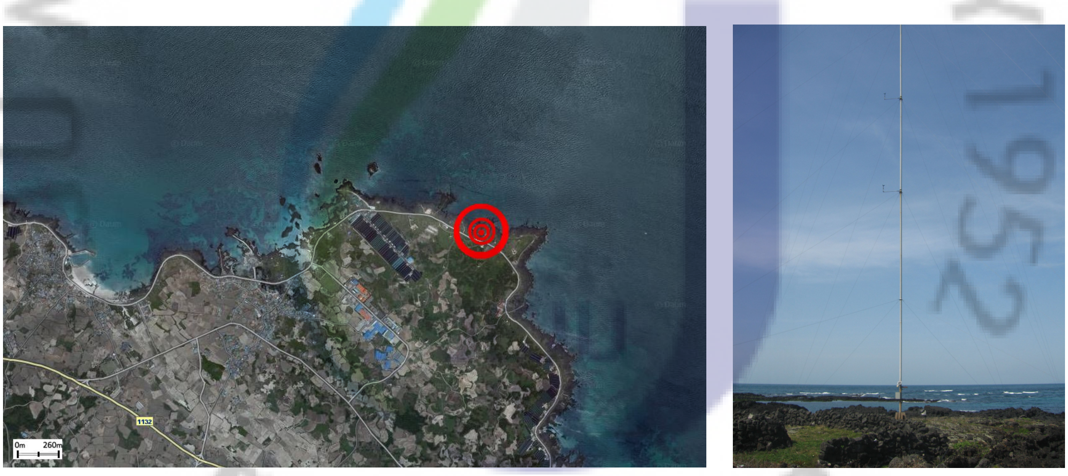

Figure 3.4 An aerial photo of Hangwon and installed met. mast

3.1.2.2 Hoichun site

Hoichun is located inland area. The Hoichun mast, which is located at a height of 400m above sea level, is girdled with gently rolling hills and small mountains named Orem. As can be seen in Figure 3.5 and 3.6, which is derived from SRTM(Ver. 3) database, the height of the site is in the range from 300m to 600m. The terrain shows a small 0.5° inclination from the north seaside towards the site and the area generally shows a characteristic of rolling-complex terrain.

Figure 3.5 Location of measurement site in Hoichun

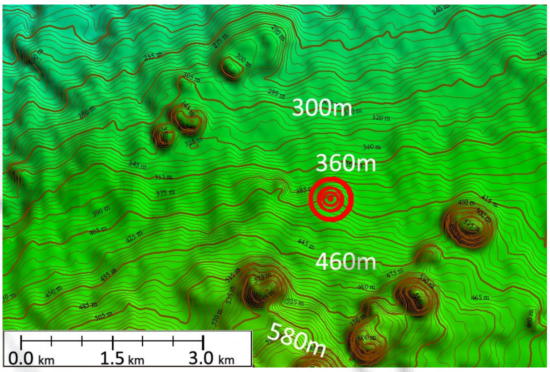

Figure 3.6 Digital terrain model of Hoichun

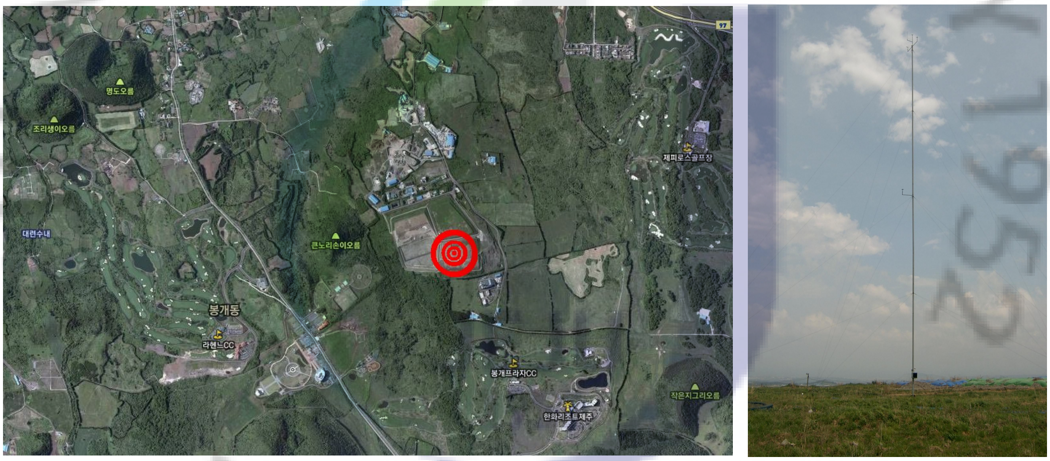

Figure 3.7 An aerial photo of Hoichun and installed met. mast

Figure 3.7 shows the aerial photo and installed meterological mast of Hoichun site. A Resource Recovery Facility is situated at 250m distance to the south-east, a few Orems which are able to affect the wind flow are located around the mast in 550m and in 2km distance to the north-west and in 1.5km distance to the south-east. A golf club was developed near the mast and forests exist, however due to their low obstacle height no significant effect was observed.

3.1.2.3 Susan site

Susan is located in the south-eastern part of Jeju. As can be seen in Figure 3.8 and 3.9, due to its characteristics surrounded by many Orems, the wind flow from east and north is significantly affected. therefore the area is classified as complex terrain. In details, Orems are located to the north side in 300m and 500m distance and also to the south-eastern direction in 1.7km distance.

Figure 3.8 Location of measurement site in Susan

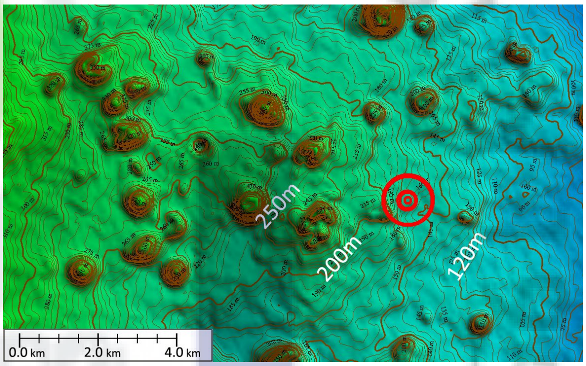

Figure 3.9 Digital terrain model of Susan

Figure 3.10 An aerial photo of Susan and installed met. mast

Figure 3.10 shows the aerial photo and installed meterological mast of Susan site. A plant community of small bushes and forest was sprawled out from the north-western to the northern-side. The mast was situated at a height of 160m above sea level. Around the mast grass land with groups of small bushes with the height of around 1m were observed.

3.2 Data sets

3.2.1 Mast data

The meteorological equipment consists of NRG data logger, type 40 anemometers, type 200 wind vanes, pressure sensors and humidity sensors. The sensors are manufactured by NRG systems and all anemometers were calibrated by Otech Engineering3).

The wind monitoring equipment was mounted on tall towers with different height according to the sites. Also the mast position was deeply considered to avoid flow distortion through terrain shapes.

Figure 3.11 Mast installation and logger type

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3) http://www.otechwind.com/

Figure 3.11 shows the installation of a measurement mast and also shows a data logger that was used. Table 3.1 shows the detailed specification of the sensors from NRG systems. Other sensors except wind anemometer and vane were used to check the quality of data.

Table 3.1 Specifications of the sensors

Sensor	Raw Sensor Output	9300 Data Output Range	9300 Resolution
Maximum #40 Anemometer	0Hz ~ 125Hz	1m/s ~ 96m/s	0.271%
200P Wind Direction vane	0V ~ excitation Voltage	360° rotation	0.271%
110S Temperature Sensor	0 ~ 2.5V	-40℃ ~ 52.5℃	0.271%
LI-200SA Li-Cor Pyranometer	93.7microamps/ 1000W/m^2	0 ~ 3000 W/m^2	0.271%
BP-20 Pressure Sensor	0 ~ 10.55kPa	15 ~ 115kPa	0.271%

3.2.1.1 Hangwon Mast

The met tower was installed from 1997 for the purpose of constructing Hangwon wind farm but after 1 year of measurement it was dismantled and reinstalled from 2002. Data was collected from 2002 but in the mean time some serious events such as typhoon, lightning strike, etc have occurred even though protection such as a lightning rod was installed. Sensors were changed a few times and as a result of that the data had inconsistency. Nevertheless to employ the data for this study, the raw data which was recorded in 10-minutes averaging intervals for one year period in 1997 and in 2006 was collected and carefully analyzed, respectively.

The wind speed and wind direction measurement height are as follows:

- Wind Anemometer : 45m/37.5m/30m/22.5m/15m
- Wind Vane : 45m/30m

Figure 3.12 shows seasonal wind speed and directional wind frequency distribution from the analysis of 45m sensor data of the year 2006.

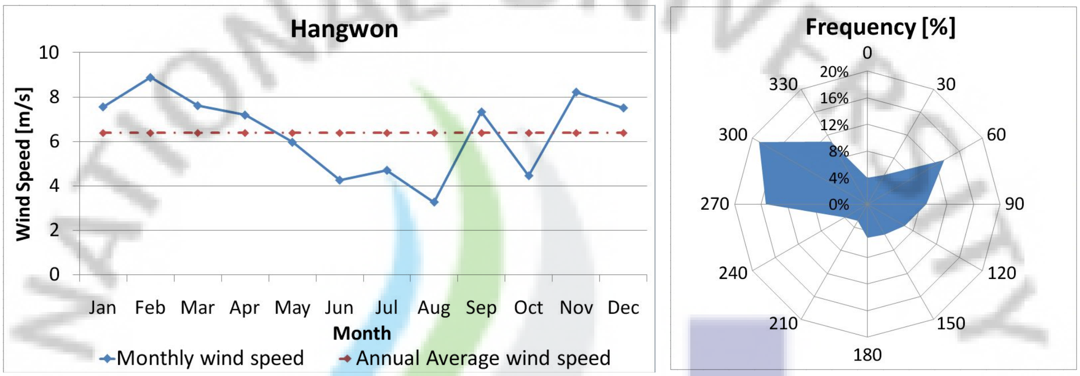

Figure 3.12 Seasonal wind speed and wind rose of Hangwon

3.2.1.2 Hoichun Mast

The met. mast was installed in Hoichun site and data was collected for several years but, after checking the quality of data, only the data from the one year period from 15/7/2005 to 1/7/2006 was chosen. The data has been recorded at 1-hour averaging intervals.

The wind speed and wind direction measurement height are as follows:

- Wind Anemometer : 30m/15m
- Wind Vane : 30m

Figure 3.13 shows seasonal wind speed and directional wind frequency from the analysis of 30m sensor data in the one-year period 15/7/2005 to 1/7/2006.

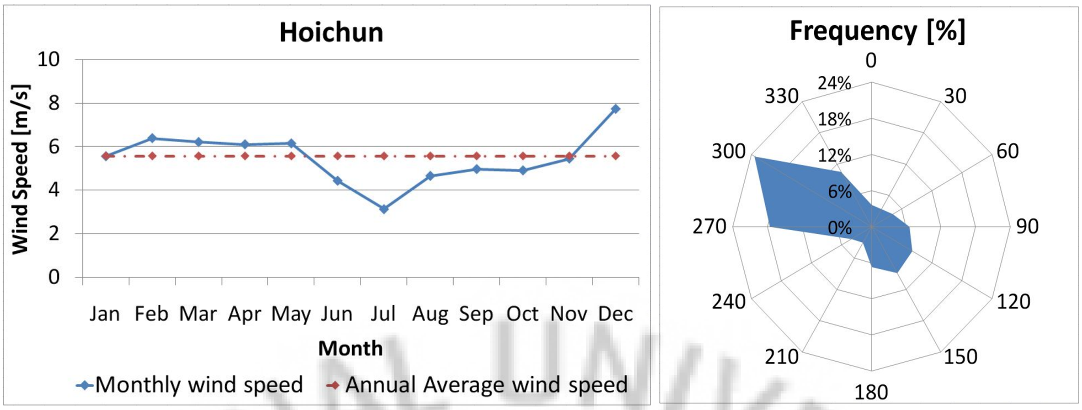

Figure 3.13 Seasonal wind speed and wind rose of Hoichun

3.2.1.3 Susan Mast

The measurement data for one year period from 1/11/2005 to 31/10/2006 was selected from the whole data of this site after checking the data quality. The data were recorded in 10-minute averaging intervals. The wind speed and wind direction measurement height are as follows:

- Wind Anemometer : 30m/15m
- Wind Vane : 30m

Figure 3.14 shows seasonal wind speed and directional wind frequency from the analysis of 30m sensor data of the one-year period 1/11/2005 ~ 31/10/2006.

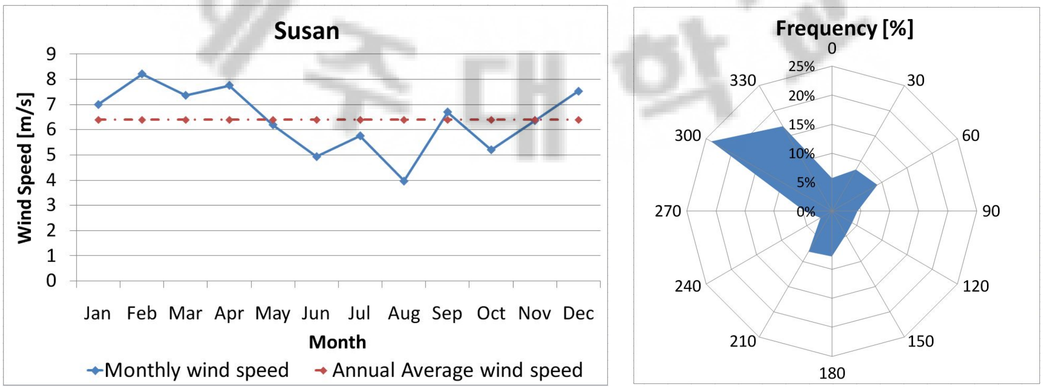

Figure 3.14 Seasonal wind speed and wind rose of Susan

3.2.2. Reference data

As the reference sites for the long-term correction by applying the MCP method, typically NCEP/NCAR reanalysis data, Automated Surface Observing System (ASOS) or AWS data operated by KMA or any other nearby mast data can be used. However, in this study only nearby AWS data was selected and as will be further outlined below.

To apply the MCP method the distance between mast and reference sites is important but data consistency, quality of data is more crucial. NCEP/NCAR reanalysis data is available in a spatial grid resolution of 2.5×2.5 degrees at time intervals of six hours. The data are based on observations that have been assimilated into a global or regional weather model. Figure 3.15 shows the points of these data nearby Jeju.

NCEP/NCAR Reanalysis data Coordinates	
P1	32° 30' N 125° 00' E
P2	32° 30' N 127° 30' E
P3	35° 00 'N 125° 00 'E
P4	35° 00' N 127° 30' E

Figure 3.15 The NCEP/NCAR Reanalysis data points nearby Jeju

The timely resolution of six-hour is too rough for application of many methods. It may be good for daily, weekly and monthly wind index methods but not for methods which work based on time series data. The rough spatial grid of 2.5x2.5 degrees must ignore any local characteristic effects. Therefore any method that uses wind direction data will not work properly with the NCEP/NCAR data, at least if terrain is complex. With respect to its consistency over time, reanalysis data do not meet the required consistency standard, because of substantial and continuing changes in the observational system used to create that data set [25],[26].

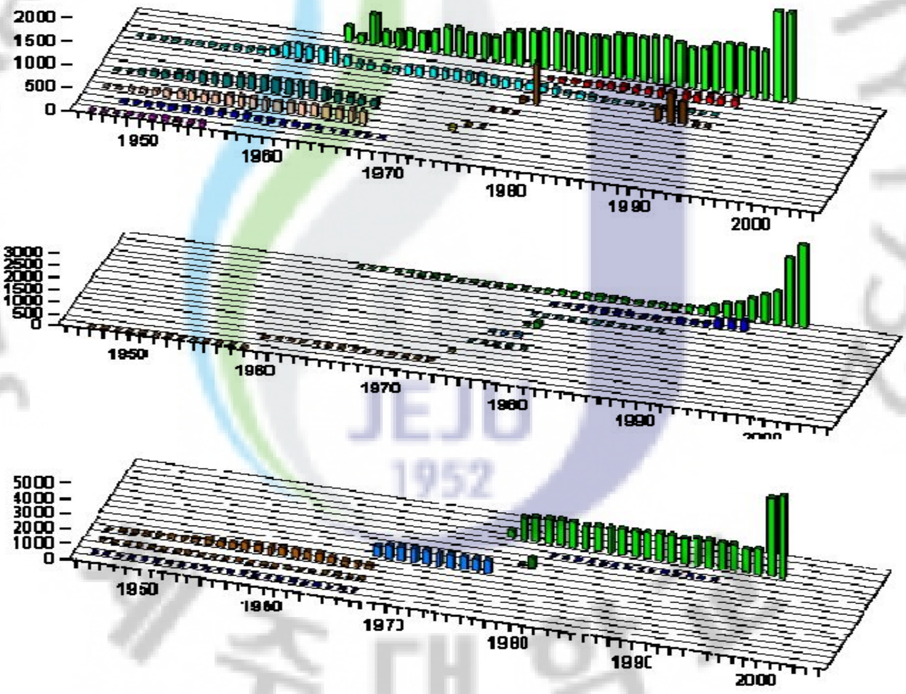

Figure 3.16 The NCEP/NCAR Reanalysis (Source: Bulletin of the American Meteorological Society(2001))

Figure 3.16 shows an inconsistency of data which was happened due to significant changes in the observational system. Inventory of Rawinsonde/pibal observations(top), aircraft observations(middle) and land surface observations (bottom) used in reanalysis from 1948 to 2000. Each row represents a different data set, the back(green) row refers to data maintained by NCEP. Units are in megabytes.

Since there was not any other reference mast nearby each measurement site, AWS data was used as reference data to compare the MCP methods. These stations are very near to the mast.

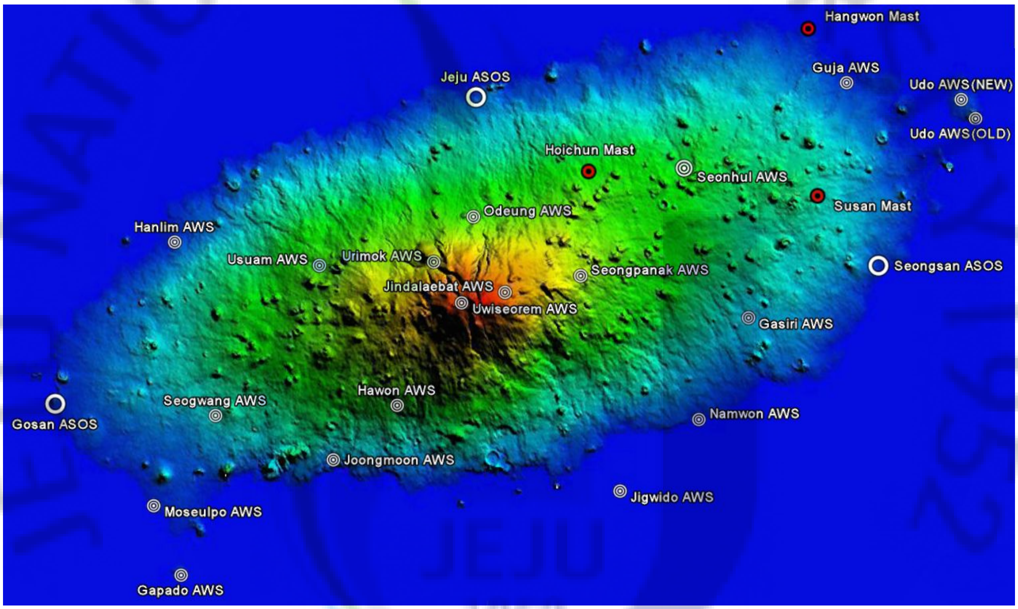

Figure 3.17 Meteorological masts and reference(AWS) sites in Jeju island

Figure 3.17 shows all ASOS and AWS positions operated by KMA in Jeju, of which a few stations were selected and correlated for this study. The distance between the masts and the selected reference sites will be shown in the next chapter.

4. Application of each method

4.1 Evaluation of usefulness of linear regression method

4.1.1 Data set

Linear regression is widely used MCP method in the wind industry because the method is more easy to use than other methods, not tricky to understand and it does not require long time to calculate. This study was carried out to find out how accurate results from the linear regression method can be achieved in Jeju island and the method has been applied two sites, namely Hangwon and Hoichun site, which are shown in Figure 4.1.

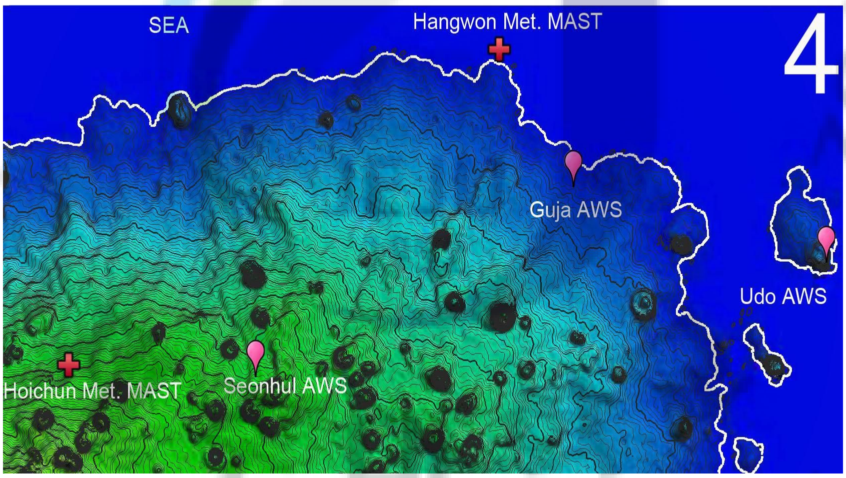

Figure 4.1 Location of meteorological masts and AWS

For testing the linear MCP method to two measurement sites and three reference sites were chosen. For the measurement data, time series wind data at each site were selected and they were filtered when invalid data were found.

Measurement site data were originally recorded as a 10 minutes averaged value and have been averaged to 1-hourly data in order to match and be comparable to the three reference site AWS data, which were only recorded as 1 hour averaged values. Basic information of the mast and reference sites is shown in Table 4.1.

Table 4.1 Measurement and reference sites

Site	Location (Lat/Lon)	Measurement Height (m)	Altitude (m)	Area Type
Hangwon (Met. Mast)	33°33′34.6″ N 126°49′17.9" E	30	0.8	coastal
Hoichun (Met. Mast)	33°27′27.4″ N 126°37′47.1″ E	30	401.4	inland
Guja (AWS)	33°31′21.4″ N 126°51′06.7″ E	10	25.3	inland
Seonhul (AWS)	33°27′30.6″ N 126°42′42.8″ E	10	341.28	inland
Udo (AWS)	33°30′23.4″ N 126°57′12.1″ E	10	135	coastal

Table 4.2 Measurement period and data recovery rates

Site	Measurement period	Data recovery rate(%)
Hangwon	'06.1. 1~ '06.12.31 (1year)	99.8
Hoichun	'06.7.1 ~ '07.6.30 (1year)	97.2
Guja	'93.3.13 ~ '08.9.30 (15years)	86
Seonhul	'93.1.1 ~ '07.12.30 (15years)	87.6
Udo	'93.1.1 ~ '06.12.31 (14years)	88.9

To minimize the uncertainties of measurement data, at least eight months of data are recommended [8] and finally one year of data period was used, which had a data recovery rate more than 97%.

Table 4.2 shows measurement periods and data recovery rates of the mast and reference sites.

4.1.2 Correlation and long-term prediction

Before performing the MCP analysis it has to be considered the correlation coefficient, r, between the sites data. As for each combination of two measurements sites and three reference sites, the correlation coefficient was calculated and based on their relationship the biggest one has been chosen for the further process.

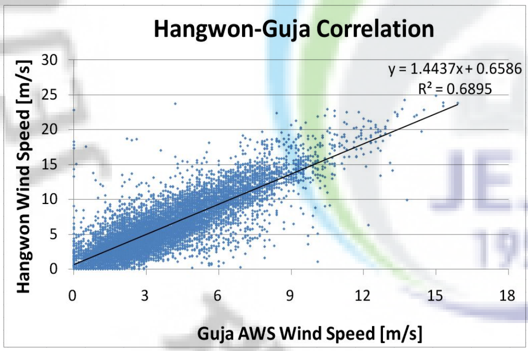

Figure 4.2 Correlation coefficient between Hangwon mast and Guja AWS

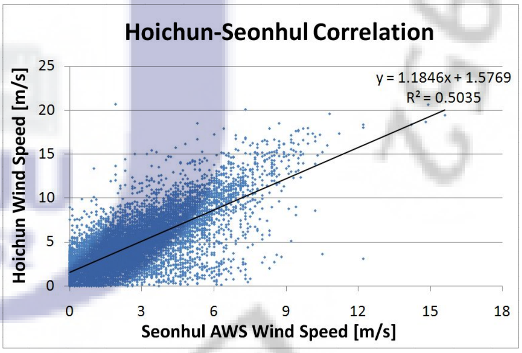

Figure 4.3 Correlation coefficient between Hoichun mast and Seonhul AWS

Figure 4.2 shows the correlation coefficient between Hangwon met. mast and Guja AWS. It is indicated that the sites have a good-correlation value of r=83% for the wind speed data. Figure 4.3 shows the correlation coefficient between Hangwon met. mast and Seonhul AWS. It is indicated the sites have a moderate-correlation value of r=71%.

In the case of Udo AWS, the correlation also shows a good correlation value, almost the same as Hangwon and Guja, with r=84%. However the position of Udo AWS was moved from the top of hills to a lower area for some reason in the year 2002, which has caused significant inconsistency of the two wind data before and after. Therefore Udo AWS data was excluded from the further analysis.

Hangwon site is 5.4km apart from Guja AWS, Hoichun site and Seonhul AWS are 7.65km away from each other.

The data of Hangwon and Hoichun sites were divided by 16 direction sectors so that each sector has 22.5 degrees. For each pair of stations the wind speed data from the measurement site, after data filtering of invalid values or suspicious outliers, were used to generate the regression line.

Moreover wind speed data below 2m/s was not used in the determination of the correlation between measurement and reference sites, as wind vane behavior is not clearly determined at low speed.

4.1.3 Predictive accuracy on both sites

4.1.3.1 Hangwon site

In Hangwon site, the concurrent wind data in the year of 2006 were used to generate a relationship between winds at both sites. This relationship has been applied to the long-term period of the reference site to predict long-term in Hangwon site.

The predicted result was evaluated on the basis of monthly average wind speeds. When comparing the measured monthly average wind speeds from 2006 with the back-predicted monthly average wind speeds for 2006, then the ratio of both will give the accuracy of the applied algorithms to describe the relationship between the measurement and the reference site.

Figure 4.4 shows the result of back prediction of Hangwon for monthly average wind speeds and monthly wind power densities. Each month has a little difference between measured and predicted data.

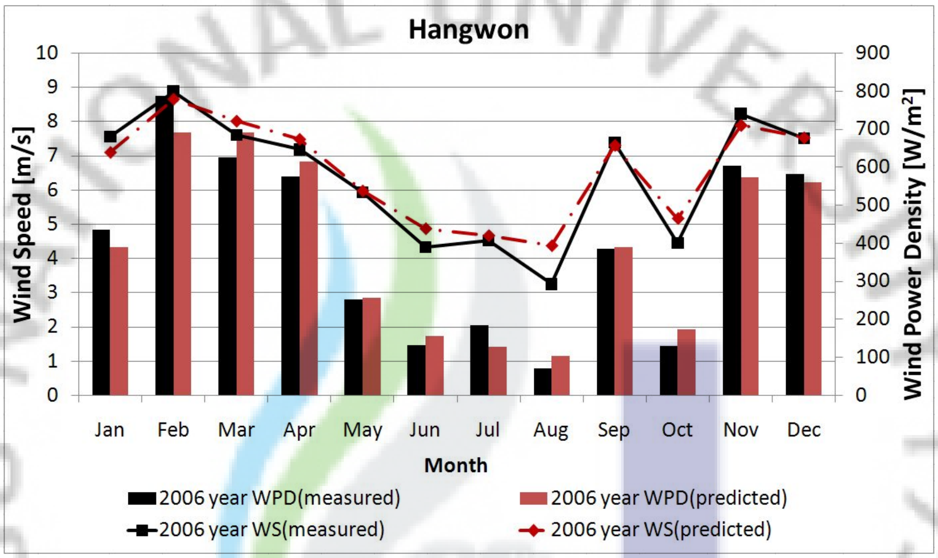

Figure 4.4 Back-Prediction of Hangwon

As another example for the period of the year 1997 Hangwon wind data was used to evaluate predictive accuracy of linear regression. By applying the relationship obtained from the 2006 Hangwon wind data, the back-prediction of the wind conditions of the previous year 1997, which will be called “previous-year-prediction” was obtained.

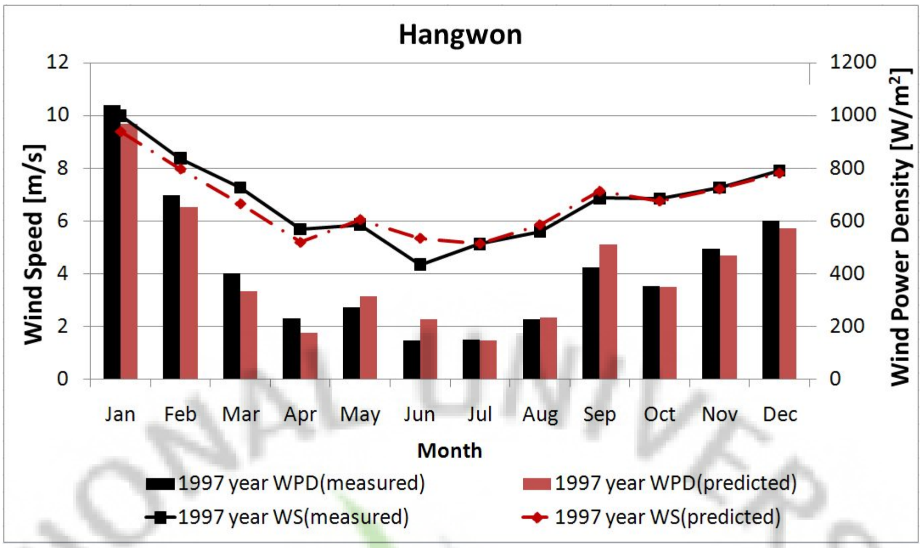

Figure 4.5 Previous-year-prediction of Hangwon

Figure 4.5 shows the result of previous-year-prediction of Hangwon based on 1997 data. It has a little difference from the 2006 based result and the same pattern as the Figure 4.4. This means that the regression model derived from concurrent data of 2006 not only back-predicts well the year of 2006 site data, but also is capable to back-predict the year of 1997 site data.

4.1.3.2 Hoichun site

For the Hoichun site, the same evaluation method as at the Hangwon site was used. The wind data from 7/2006 to 6/2007, which is regarded as “concurrent data”, was analyzed for Hoichun site.

Figure 4.6 shows the result of back-prediction of Hoichun which has a little difference for monthly average wind speeds and monthly wind power densities.

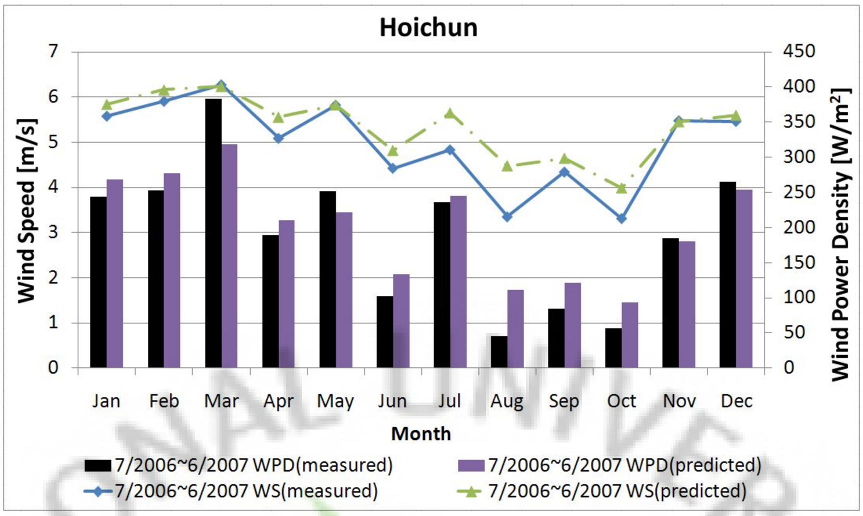

Figure 4.6 Back-prediction of Hoichun

Figure 4.7 shows the result of previous-year-prediction of Hoichun from 7/2005 to 6/2006. It has a fairly certain difference in both monthly wind speed and monthly wind power density.

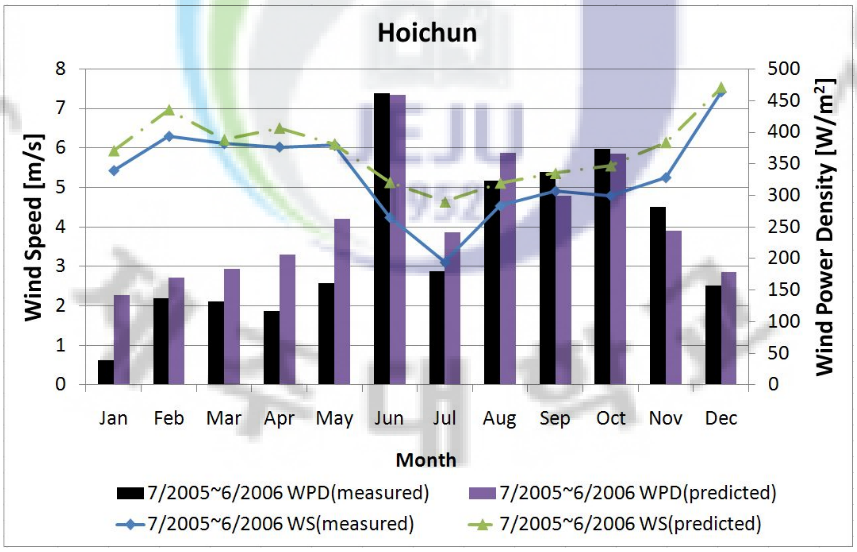

Figure 4.7 Previous-year-prediction of Hoichun

Added to this, to assess predictive accuracy the Relative error was calculated, which is given by

$$Relative\ error = \frac{True\ value - Predicted\ value}{True\ value} \qquad 3)$$

Table 4.3 Relative error of each site

Site		Back-prediction		Previous-year-prediction	
		V [m/s]	WPD [W/m^2]	V [m/s]	WPD [W/m^2]
Hangwon	Measured	6.44	402	6.75	419
	Predicted	6.58	392	6.82	426
	Error (%)	-2.03	2.53	-0.95	-1.77
Hoichun	Measured	4.98	191	5.44	232
	Predicted	5.36	203	5.97	259
	Error (%)	-7.53	-6.60	-9.70	-11.41

Table 4.3 shows the comparison of error ranges between simple and mountainous terrain.

In Hangwon site as a simple terrain, the error is estimated within the range of ±2.5% in monthly wind speed and monthly wind power density. The relative error between measured and predicted wind data for wind speed was estimated from -2.03% to -0.95% and the error for wind power density was estimated from -1.77% to 2.53%.

In Hoichun site as a mountainous terrain, the error is estimated within the range of ±8% in monthly wind speed and ±12% in monthly wind power density. As can be seen Table 4.3, the relative error between measured and predicted wind data for wind speed was estimated from -9.73% to -7.53% and the error for wind power density was estimated from -11.41% to -6.60% .

Despite of the short distance between the measurement and the reference site pairs used in this study, the linear regression method showed relatively large prediction errors in mountainous terrain. It worked well with relatively small prediction errors in more simple terrain.

4.2 Comparison of different MCP methods

In this section three different MCP methods, i.e. the linear regression method and two alternative MCP methods were compared using the wind data at different sites. Three different sites are Hangwon, Hoichun and Susan sites, which are shown in Figure 4.8. Susan sites are selected for the more complex terrain than Hoichun.

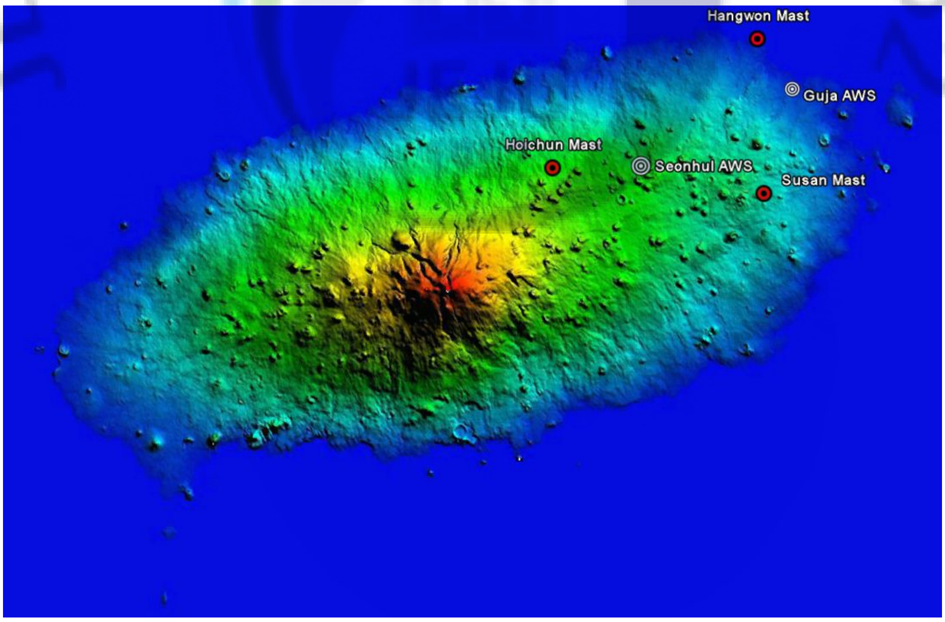

Figure 4.8 Location of met. masts and AWS

4.2.1 Wind data sets

To compare MCP methods between different site conditions, time series wind data at each site were selected and they were filtered when unreliable or wrong data such as flagged ones, wrong time sequence, etc were found.

In the case of AWS data, from the beginning stage of measurement, it was happened many data losses and to keep the high data recovery rate, early year data are discarded deliberately. As a result, the long-term measurement period was reduced to 12 years from 15 years, but the recovery rate of data in the considered period was increased from 87.6% to 96.7% in the case of Seonhul. It also increased in the case of Guja.

To minimize the seasonality and other factors, around one full year of data were used at every target site and in each case. They recovered more than 97% of data. Table 4.4 shows basic information of three target sites and AWS reference sites.

Table 4.4 Wind Characteristics summary of each site

Site		Mast			AWS	
		Hangwon	Hoichun	Susan	Seonhul	Guja
Measurement period (year)		'06.1.1～ '06.12.31(1)	'05.7.15～ '06.6.30 (1)	'05.11.1～ '06.10.31(1)	'97.1.1～ '09.7.31(12)	'98.1.1～ '09.7.31(11)
Data Recovery Rate (%)		100	97.8	100	96.7	99.2
Mean wind speed (m/s)		6.39@45m	5.56@30m	6.4@30m	3.16@10m	4.04@10m
Wind shear Exponent		0.0675	0.237	0.134	-	-
Weibull Parameter	A	7.073	6.203	7.204	3.483	4.483
	k	1.549	1.632	1.966	1.497	1.589
Prevailing wind Direction		NW/WNW	WNW/W	NW	N/NW	NW

4.2.2 Correlation coefficient

To make a concurrent data set, each measurement site data was averaged hourly following the AWS data sets and then one out of two AWS was selected to be used as a reference site data by comparing their correlation coefficients.

Table 4.5 and 4.6 shows the correlation coefficient between measurement and reference sites. Seonhul AWS was chosen as a reference for all measuring sites because the correlation value of this station appeared very similar with all measuring stations. Even though Guja AWS had a higher correlation with two of measuring sites, there is a big variation of the correlation value. As the aim of this study is to compare the performance of MCP methods among each other it is preferable to have similar correlation values for each pair of stations in order to avoid biasing of results from different correlation performance. Accordingly the three different concurrent data sets were made using Seonhul AWS.

Table 4.5 Correlation coefficient between measurement and reference sites [%]

Reference / Measurement	Seonhul	Guja
Hangwon	70.63	84.73
Hoichun	73.78	66.64
Susan	72.78	75.56

Table 4.6 Correlation Index (Source: EMD)[4]

Correlation Coefficient	Quality of reference
0.9~1.0	Very Good
0.8~0.9	Good
0.7~0.8	Moderate
0.6~0.7	Poor
0.5~0.6	Very Poor

Figure 4.9 shows the distance from each mast to the Seonhul AWS.

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[4] WindPRO: Software and User Manual, Available through EMD International A/S, www.windpro.com or www.emd.dk

The distance of Seonhul AWS to all three masts is near.

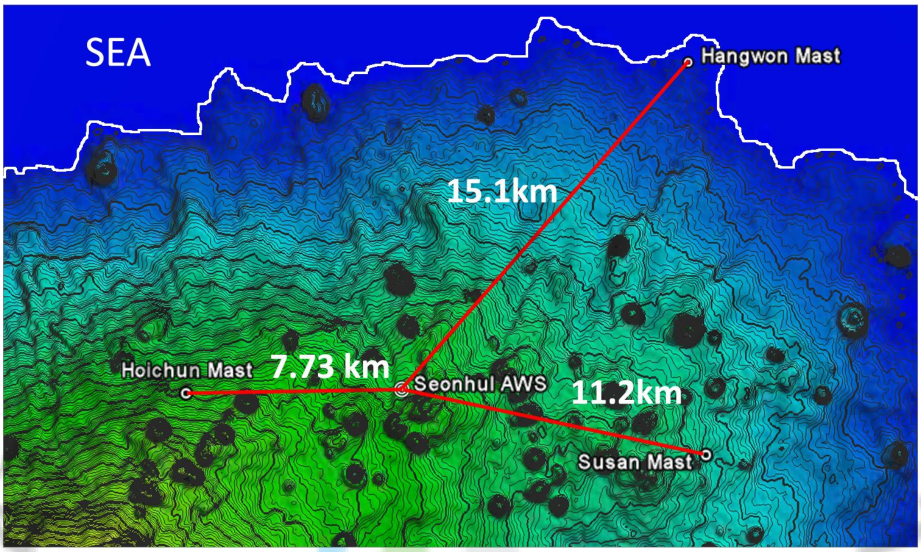

Figure 4.9 Distance between masts and reference site

4.2.3 Evaluation

To evaluate the usefulness of each MCP method the following have been compared:

1) mean wind speed
2) wind direction
3) Weibull parameters

4.2.3.1 Wind veering of each site

The wind veering is defined as the difference of the concurrent wind directions measured at two sites. When comparing hourly mean wind directions at both sites, and considering the short distances between the sites considered, the time shift effects due to advection of wind flow should be widely suppressed. Thus comparing the veering of concurrent wind data in this case will give a clear indication about the complexity of each site.

The following Figures 4.10 to 4.12 show veer angle plots between the target and the reference sites. In the Figures the large red-circles indicate the mean difference for the reference bearing bins.

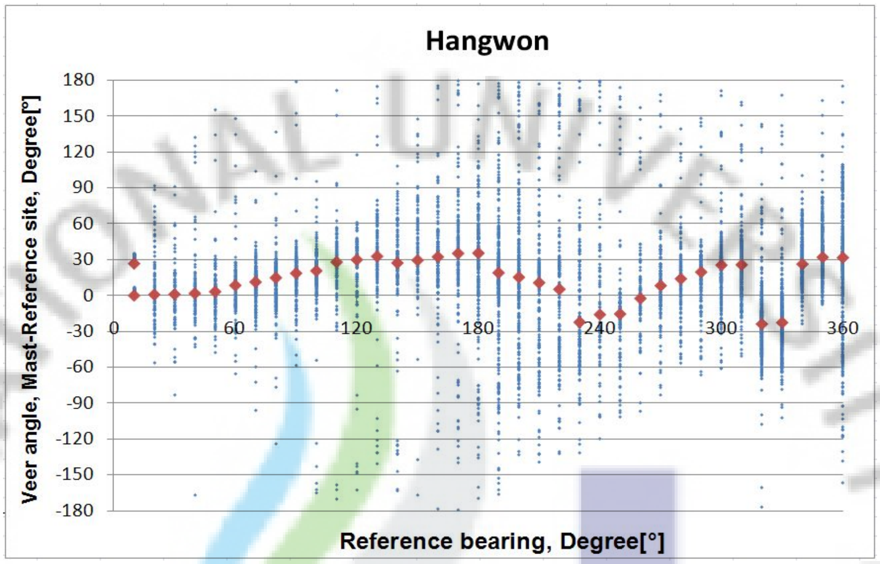

Figure 4.10 Veer plot of wind direction at mast and reference site for Hangwon

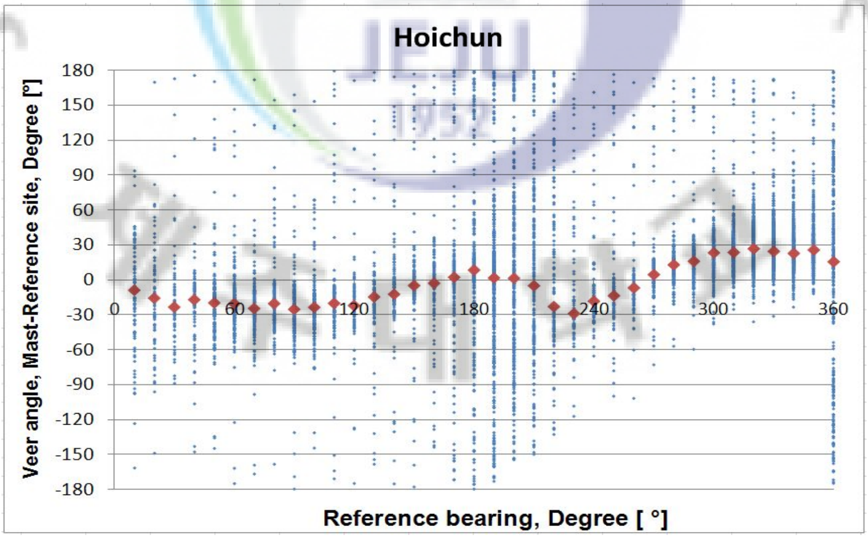

Figure 4.11 Veer plot of wind direction at mast and reference site for Hoichun

Though Hangwon has flat terrain near the sea, the Figure 4.10 shows a little wind direction deviations between 120°~180° and 270°~360°. It is considered that this is caused by complexity of the terrain around the reference site and it is meaningful because the prevailing wind direction at Hangwon is from 270° to 330°.

Figure 4.11 shows wind veering between 300°~330°, which is matching well with prevailing wind direction at Hoichun.

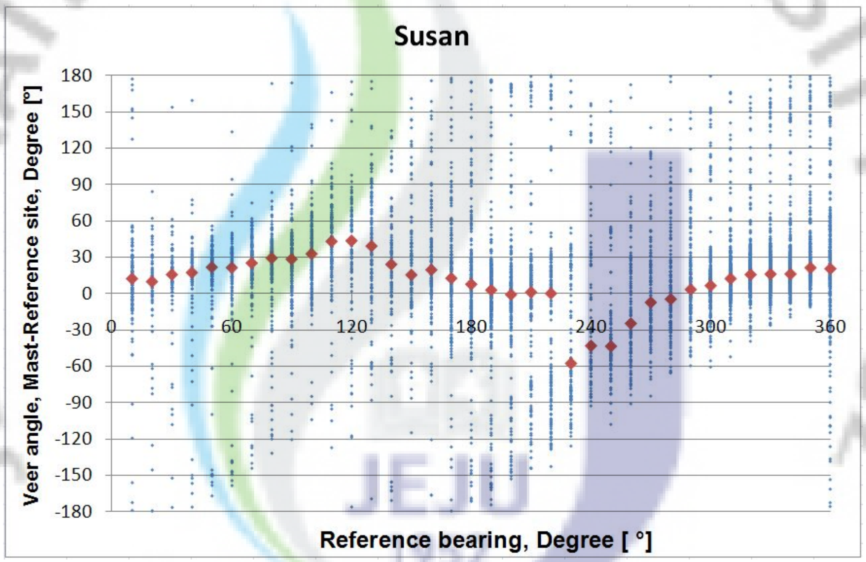

Figure 4.12 Veer plot of wind direction at mast and reference site for Susan

Figure 4.12 shows the wind veering of Susan, with prevailing winds blowing from 300°~330°. In this figure the most significant wind veering happens between 100°~140° and 210°~250° but this is less important because this directions shows low wind speed and low frequency. These only have minor effect on calculating wind energy of the Susan site.

4.2.3.2. Wind speed and direction of each site

Table 4.7 shows the comparison result between measured and long-term predicted values of mean wind speed for site. In this table the measured wind speed is just one year data but for use of comparison it is assumed that this value is the same as the long-term value of each site. The reason is that longer periods(such as 10 years) of wind measurement data cannot be found in Korea. Furthermore, in case of Hangwon data a period of 6 years has been available and was tested to compare but it showed almost the same result, which is shown in Table 4.8 further below. Therefore the one year value was considered for all stations.

Table 4.7 Comparison of measured and predicted mean wind speed of each site

Method / Site	Measured (m/s)	Predicted		
		Linear	Matrix	Joint probability
Hangwon	6.39	6.55	6.85	6.66
Correction factor (%)	-	+2.50	+7.20	+4.22
Hoichun	5.56	5.42	5.09	5.45
Correction factor (%)	-	-2.51	-8.45	-1.97
Susan	6.39	6.46	6.76	6.43
Correction factor (%)	-	+1.10	+5.80	+0.63

The values derived from all three methods are consistent in so far that all methods indicate an upscale correction in order to make the measured data period long-term representative. The upscale correction factor[5]s are ranging from +2.5% (Linear) to +7.2% (Matrix) with the Joint probability method in between at +4.2%. As previously discussed a reliable estimation of the

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[5] Correction factor shows the result of the long-term correction in terms of the ratio between predicted and measured mean wind speed and it may be simply called as a long-term correction factor or long-term scaling.

predictive accuracy would require about 10 years of measured data, which is not available. However, using the available 6-year data period has lead to similar correction factors, which indicates that the lower correction factors are more appropriate as can be seen in Table 4.8.

Table 4.8 Comparison of measured and predicted mean wind speed of Hangwon, using 6-year measured data

Method / Site	Measured (m/s)	Predicted		
		Linear	Matrix	Joint probability
Hangwon	6.48	6.55	6.85	6.66
Correction factor (%)	-	+1.08	+5.71	+2.77

In mountainous terrain like Hoichun and Susan, the predictive accuracy of the long-term wind speed cannot be judged because only one year of data is available for those stations.

Figure 4.13 shows the comparison of wind direction between measured and predicted values by three different methods. It basically shows the accuracy of algorithms of each method for describing the relationship between target and reference site because long-term wind directions are not known as previously explained. It also shows that both Matrix and Joint probability methods are very capable for predicting wind direction at least in simple terrain like Hangwon and Joint probability method maybe even slightly better than Matrix in the case of the 270° Sector. On the other hand, the Linear method cannot predict the wind direction distribution at the target site. This is because the linear method assumes that wind directions at the reference and the target site are the same and thus wind direction is ignored by the concept of this method.

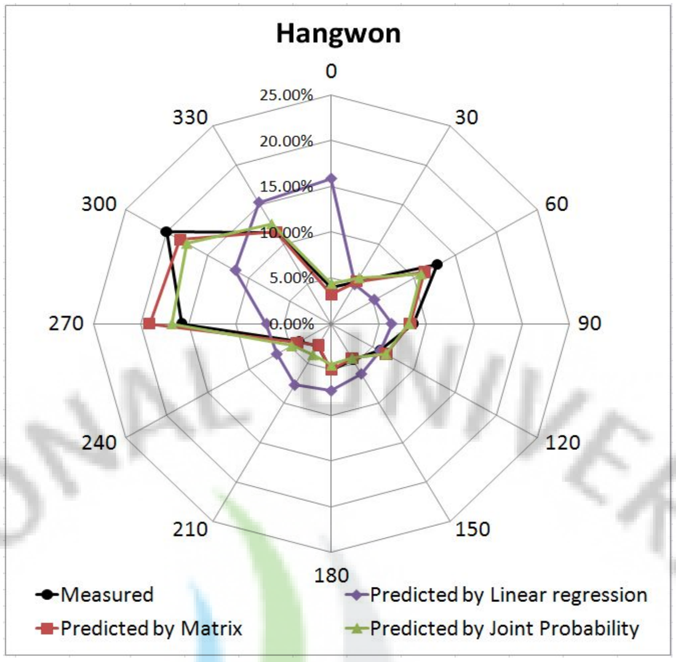

Figure 4.13 Comparison of wind direction in each sector between measured and predicted in Hangwon

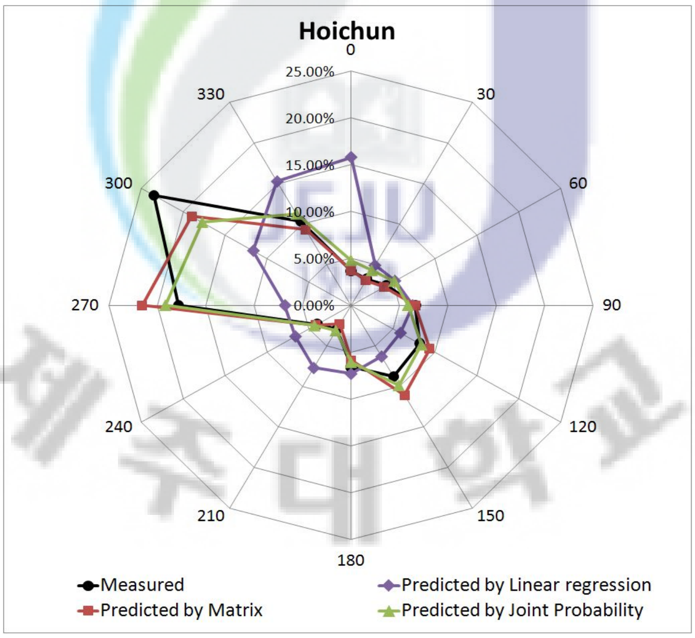

Figure 4.14 Comparison of wind direction in each sector between measured and predicted in Hoichun

Figure 4.14 shows that matrix and joint probability methods are in good agreement with measured data but in case of Linear regression method, it shows very poor agreement. It basically shows the accuracy of algorithms of each method for describing the relationship between measuring and reference site because long-term wind directions are not known as previously explained.

It also shows that both Matrix and Joint probability methods are very capable for predicting wind direction in semi-complex mountainous terrain like Hoichun and Joint probability method slightly better than Matrix when looking at some specific sectors. On the other hand, the linear method cannot predict the wind direction distribution at the target site. This is because the linear method assumes that wind directions at the reference and the target site are the same and thus wind direction is ignored by the concept of this method.

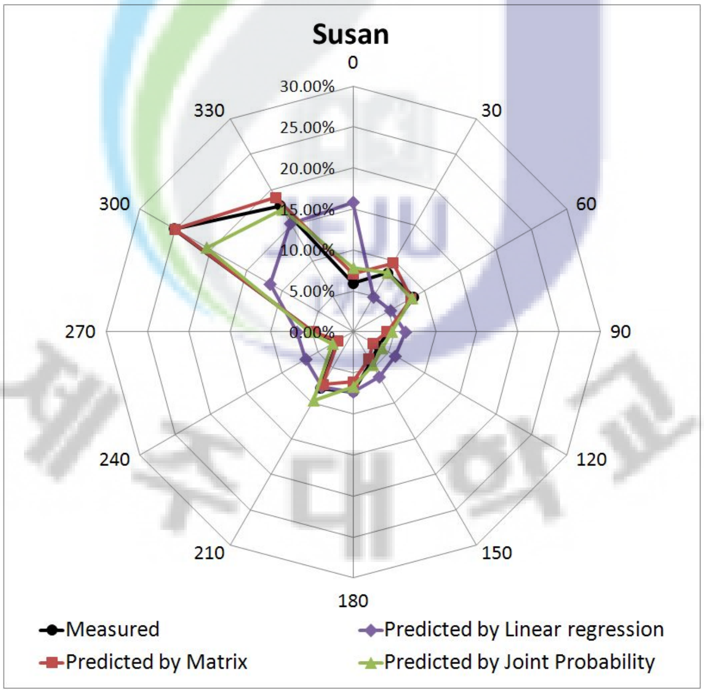

Figure 4.15 Comparison of wind direction in each sector between measured and predicted in Susan

Figure 4.15 shows the result of comparing wind direction between measured and predicted by three different methods in Susan. It basically shows the accuracy of algorithms of each method for describing the relationship between measuring and reference site because long-term wind directions are not known as previously explained.

It also shows that both Matrix and Joint probability methods are very capable for predicting wind direction even in mountainous-complex terrain like Susan and here the Matrix method performs better than Joint probability in the prevailing wind direction sectors. Nevertheless, in average including all sectors the performance of both methods is quite equal. Again, due to its concept the Linear method cannot predict the wind direction distribution at the target site. The details of directional frequency of each site can be found in Appendix D.

4.2.3.3. Weibull parameters

Power production of a wind turbine generator is calculated from a power curve, which is a measured characteristic of a wind turbine, and from a probability density function of the wind speeds at the site [27],[28].

The wind speed distribution at a site can be represented by the Weibull function $f(V)$.

$$f(V)=\frac{k}{A}\left(\frac{V}{A}\right)^{k-1}exp\left[-\left(\frac{V}{A}\right)^{k}\right] \qquad 4)$$

where k is the shape parameter, A is the scale parameter of the distribution [29].

To evaluate the three different MCP methods, Weibull parameters were derived from WAsP(Wind Atlas Analysis and Application Program).

Table 4.9 Comparison of measured and predicted Weibull parameters

Method Site		Measured	Predicted		
			Linear	Matrix	Joint probability
Hangwon	K	1.6	1.83	-	1.6
	Error(%)	-	+14.4	-	0
	A(m/s)	7.1	7.2	-	7.3
	Error(%)	-	+1.4	-	+2.8
Hoichun	K	1.72	1.9	-	1.73
	Error(%)	-	+10.5		+0.6
	A(m/s)	6.3	6.0	-	6.2
	Error(%)	-	-4.8		+1.6
Seonhul	K	1.98	2.38	-	2.11
	Error(%)	-	+20.2		+6.6
	A(m/s)	7.2	7.1	-	7.3
	Error(%)	-	-1.4		+1.4

Table 4.9 shows the result of comparing measured and predicted values of Weibull parameters by three different methods. Larger errors, i.e. discrepancies between measured and predicted values indicate that in such case the Weibull distribution of the site data is not well maintained by a method.

As can be seen in Table 4.9, the Joint probability method predicted more accurately for both k and A of Weibull parameters. The linear regression method predicted quite accurately the scale parameter but in shape parameters it showed big difference between values compared to the measured data and compared to the predictions from the Joint probability method.

Thereby the joint probability method performed significantly better than the linear method, in particular for the shape parameter. Using the matrix method, it is impossible to get Weibull parameters due to the concept of this method. The details of directional Weibull parameters of each site can be found in Appendix E.

5. Conclusions and future work

5.1 Conclusions

In this study three MCP methods were selected and applied to simple area and mountainous area in Jeju island.

The results may be summarized as follows :

First, a linear regression MCP method was applied to predict long-term wind resource on simple and mountainous terrain in Jeju island. The result showed that the relative errors of back-prediction and previous-year-prediction of mean wind speed and wind power density in simple terrain were estimated within the range of ±3%. In mountainous terrain the relative errors for each case were estimated within the range of ±12%. Accordingly, though linear regression MCP method is useful in simple terrain it may have a large prediction error in complex terrain.

Secondly, three different MCP methods were applied to the three different terrain types to compare their performance. It was shown that matrix and joint probability methods are more useful in mountainous terrain than linear regression method because these methods are considering wind direction. Also it was concluded as follows :

Linear regression is easy to use and apply to long-term reference data regardless of hourly, daily or monthly data. However the method is not recommended to be used in mountainous terrain because the wind direction which is an important factor to construct wind farm is not considered.

The matrix method predicts the relative frequency and the mean wind speed for each direction sector at the target site, more accurately. On the other hand, it does not produce a long-term adjusted time series data set for the target site, as it is done by the linear and joint probability methods.

It is known that the joint probabilistic method is achieving more accurate prediction for wind speed and direction in both simple and complex terrain. However it was found in the process of application of the joint probability method that if the concurrent measurement period is too short, then many non overlapping data in the joint probability mass function reduced the accuracy.

5.2 Future work

According to the Korean Government strategy, more and more wind farm will be installed onshore and offshore also in Jeju island. To predict wind energy more accurately, various MCP methods need to be applied with the aim to find the most suitable and best method for Jeju island. On the basis of the results, a new method has to be developed. MCP technique is an important step in the process of wind resource assessment. This study only dealt with the comparison of methods with regard to their performance but not with the uncertainty of their application. Due to the various calculation processes of each method their magnitude of uncertainty of the derived results may be different. Therefore uncertainty to use MCP methods and further total uncertainty in wind resource assessment will be considered as a future work.

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Appendices

Appendix A Scatter plot and Joint probability Distribution of Hangwon

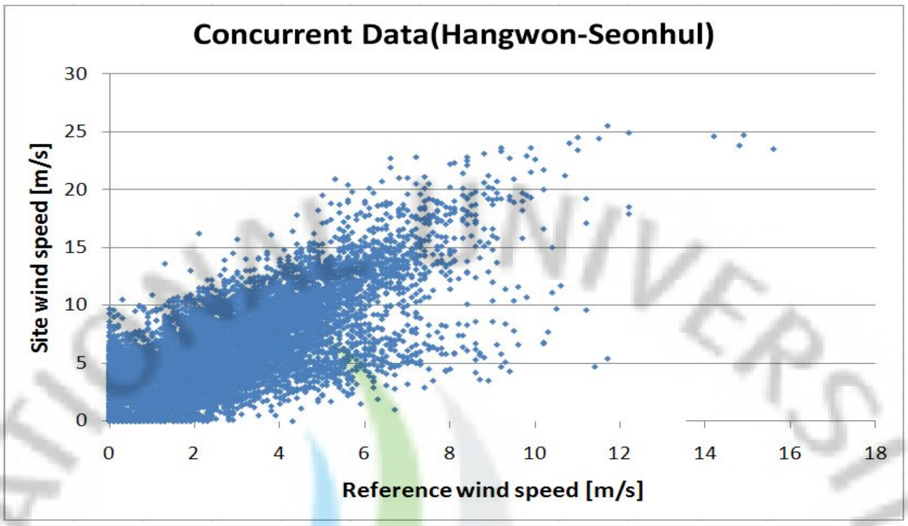


Figure A.1 Scatter plot of concurrent data for a wind direction sector

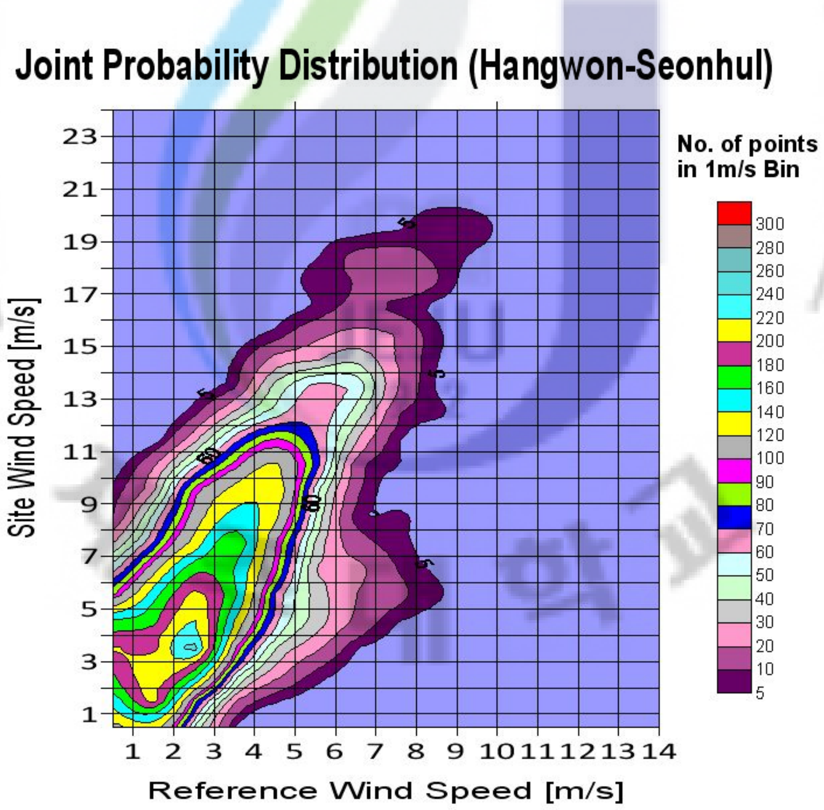


Figure A.2 Joint probability distribution of concurrent data for a wind direction sector

Appendix B Scatter plot and Joint probability Distribution of Hoichun

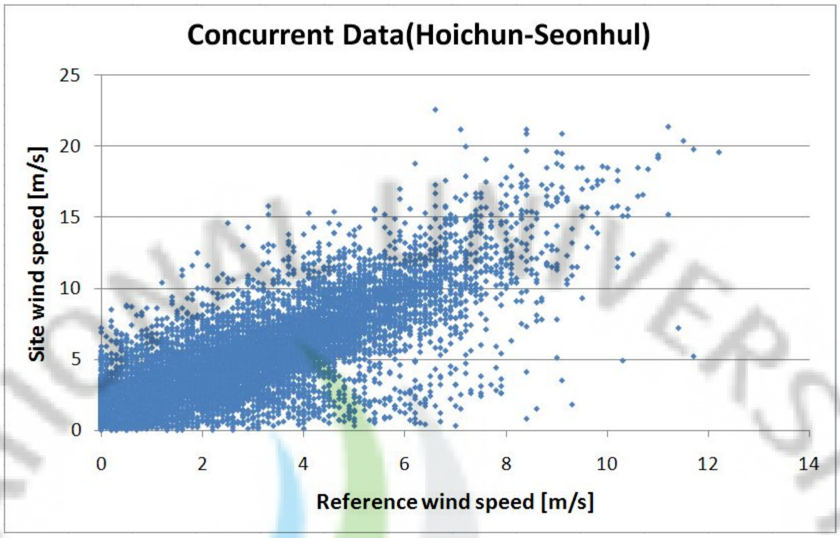


Figure B.1 Scatter plot of concurrent data for a wind direction sector

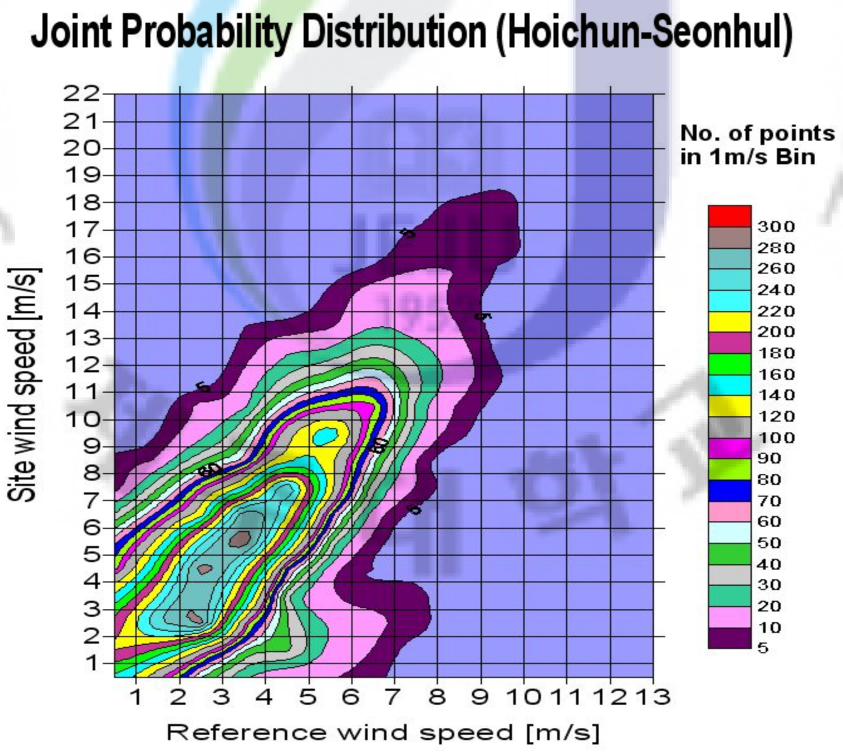


Figure B.2 Joint probability distribution of concurrent data for a wind direction sector

Appendix C Scatter plot and Joint probability Distribution of Susan

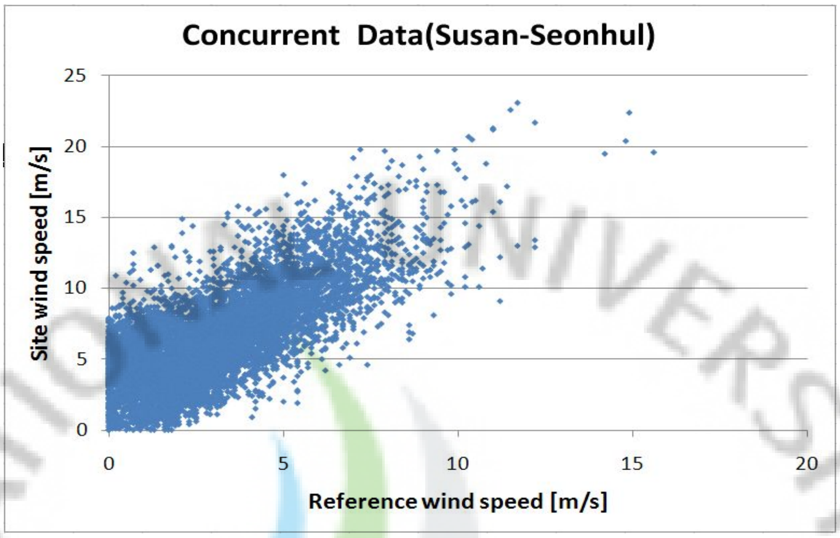


Figure C.1 Scatter plot of concurrent data for a wind direction sector

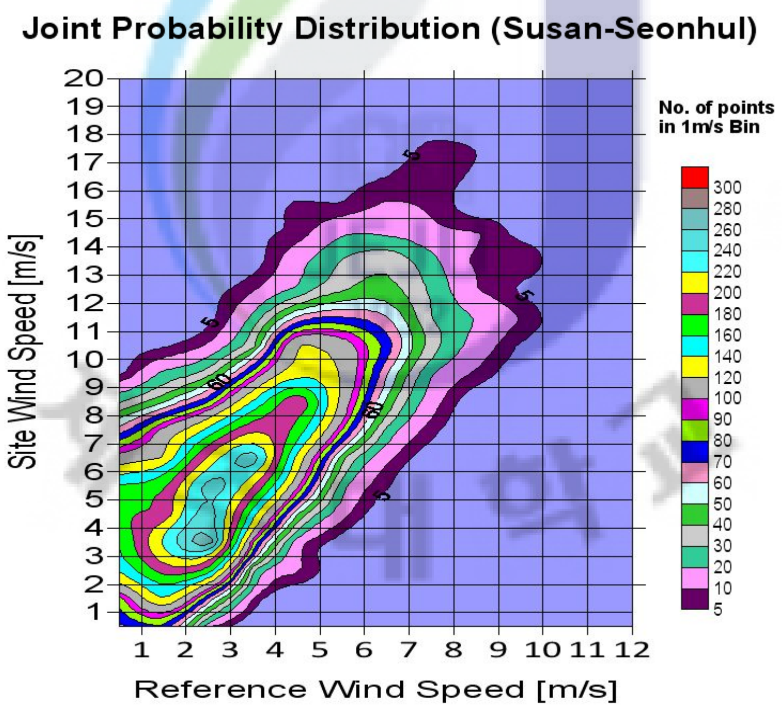
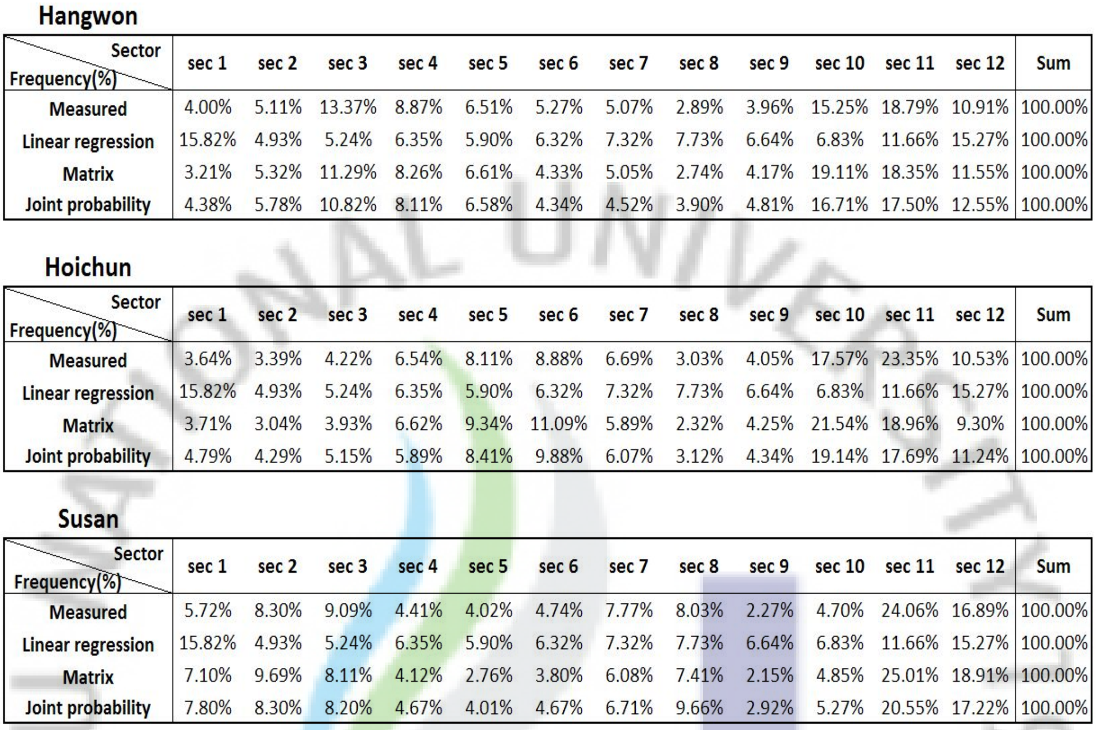


Figure C.2 Joint probability distribution of concurrent data for a wind direction sector

Appendix D Wind directional frequency of each site by three different methods



Hangwon

Sector Frequency(%)	sec 1	sec 2	sec 3	sec 4	sec 5	sec 6	sec 7	sec 8	sec 9	sec 10	sec 11	sec 12	Sum
Measured	4.00%	5.11%	13.37%	8.87%	6.51%	5.27%	5.07%	2.89%	3.96%	15.25%	18.79%	10.91%	100.00%
Linear regression	15.82%	4.93%	5.24%	6.35%	5.90%	6.32%	7.32%	7.73%	6.64%	6.83%	11.66%	15.27%	100.00%
Matrix	3.21%	5.32%	11.29%	8.26%	6.61%	4.33%	5.05%	2.74%	4.17%	19.11%	18.35%	11.55%	100.00%
Joint probability	4.38%	5.78%	10.82%	8.11%	6.58%	4.34%	4.52%	3.90%	4.81%	16.71%	17.50%	12.55%	100.00%

Hoichun

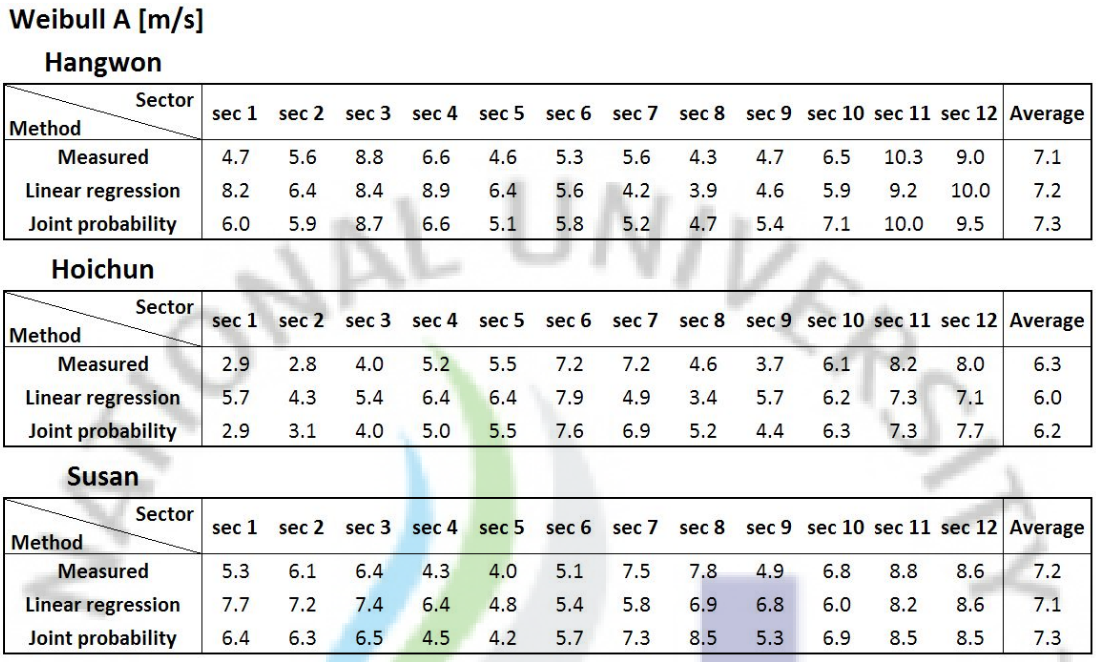
Sector Frequency(%)	sec 1	sec 2	sec 3	sec 4	sec 5	sec 6	sec 7	sec 8	sec 9	sec 10	sec 11	sec 12	Sum
Measured	3.64%	3.39%	4.22%	6.54%	8.11%	8.88%	6.69%	3.03%	4.05%	17.57%	23.35%	10.53%	100.00%
Linear regression	15.82%	4.93%	5.24%	6.35%	5.90%	6.32%	7.32%	7.73%	6.64%	6.83%	11.66%	15.27%	100.00%
Matrix	3.71%	3.04%	3.93%	6.62%	9.34%	11.09%	5.89%	2.32%	4.25%	21.54%	18.96%	9.30%	100.00%
Joint probability	4.79%	4.29%	5.15%	5.89%	8.41%	9.88%	6.07%	3.12%	4.34%	19.14%	17.69%	11.24%	100.00%

Susan

Sector Frequency(%)	sec 1	sec 2	sec 3	sec 4	sec 5	sec 6	sec 7	sec 8	sec 9	sec 10	sec 11	sec 12	Sum
Measured	5.72%	8.30%	9.09%	4.41%	4.02%	4.74%	7.77%	8.03%	2.27%	4.70%	24.06%	16.89%	100.00%
Linear regression	15.82%	4.93%	5.24%	6.35%	5.90%	6.32%	7.32%	7.73%	6.64%	6.83%	11.66%	15.27%	100.00%
Matrix	7.10%	9.69%	8.11%	4.12%	2.76%	3.80%	6.08%	7.41%	2.15%	4.85%	25.01%	18.91%	100.00%
Joint probability	7.80%	8.30%	8.20%	4.67%	4.01%	4.67%	6.71%	9.66%	2.92%	5.27%	20.55%	17.22%	100.00%

Figure D.1 Wind directional frequency of each sites

Appendix E Directional Weibull parameters of each site



Weibull A [m/s]

Hangwon

Sector Method	sec 1	sec 2	sec 3	sec 4	sec 5	sec 6	sec 7	sec 8	sec 9	sec 10	sec 11	sec 12	Average
Measured	4.7	5.6	8.8	6.6	4.6	5.3	5.6	4.3	4.7	6.5	10.3	9.0	7.1
Linear regression	8.2	6.4	8.4	8.9	6.4	5.6	4.2	3.9	4.6	5.9	9.2	10.0	7.2
Joint probability	6.0	5.9	8.7	6.6	5.1	5.8	5.2	4.7	5.4	7.1	10.0	9.5	7.3

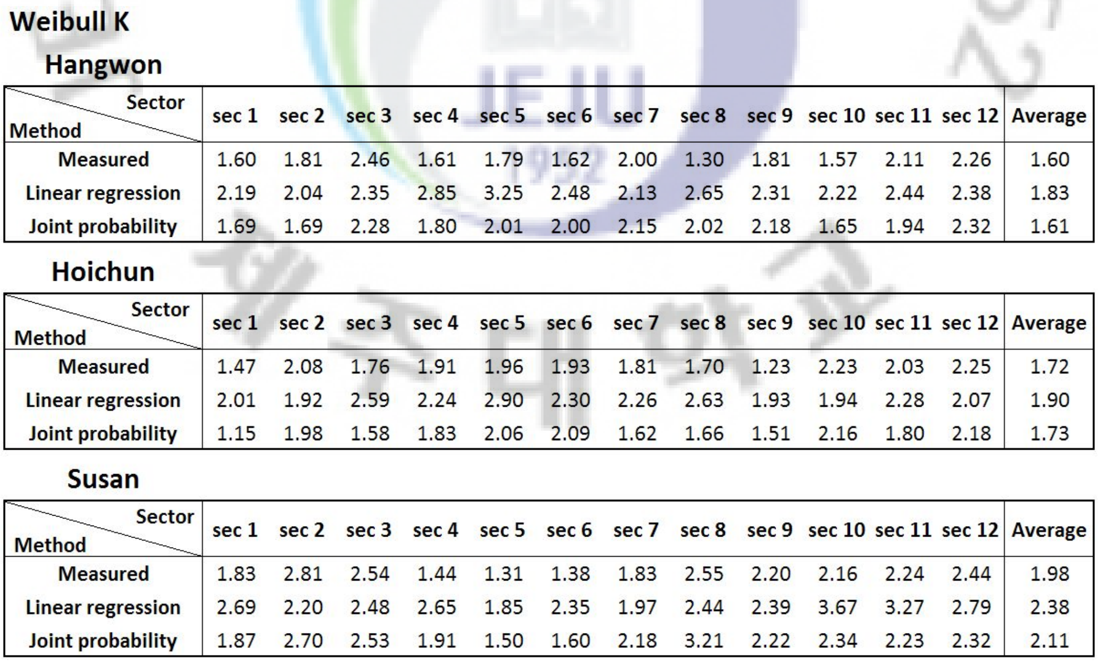
Hoichun

Sector Method	sec 1	sec 2	sec 3	sec 4	sec 5	sec 6	sec 7	sec 8	sec 9	sec 10	sec 11	sec 12	Average
Measured	2.9	2.8	4.0	5.2	5.5	7.2	7.2	4.6	3.7	6.1	8.2	8.0	6.3
Linear regression	5.7	4.3	5.4	6.4	6.4	7.9	4.9	3.4	5.7	6.2	7.3	7.1	6.0
Joint probability	2.9	3.1	4.0	5.0	5.5	7.6	6.9	5.2	4.4	6.3	7.3	7.7	6.2

Susan

Sector Method	sec 1	sec 2	sec 3	sec 4	sec 5	sec 6	sec 7	sec 8	sec 9	sec 10	sec 11	sec 12	Average
Measured	5.3	6.1	6.4	4.3	4.0	5.1	7.5	7.8	4.9	6.8	8.8	8.6	7.2
Linear regression	7.7	7.2	7.4	6.4	4.8	5.4	5.8	6.9	6.8	6.0	8.2	8.6	7.1
Joint probability	6.4	6.3	6.5	4.5	4.2	5.7	7.3	8.5	5.3	6.9	8.5	8.5	7.3

Figure E.1 Directional Weibull parameter A of each site



Weibull K

Hangwon

Sector Method	sec 1	sec 2	sec 3	sec 4	sec 5	sec 6	sec 7	sec 8	sec 9	sec 10	sec 11	sec 12	Average
Measured	1.60	1.81	2.46	1.61	1.79	1.62	2.00	1.30	1.81	1.57	2.11	2.26	1.60
Linear regression	2.19	2.04	2.35	2.85	3.25	2.48	2.13	2.65	2.31	2.22	2.44	2.38	1.83
Joint probability	1.69	1.69	2.28	1.80	2.01	2.00	2.15	2.02	2.18	1.65	1.94	2.32	1.61

Hoichun

Sector Method	sec 1	sec 2	sec 3	sec 4	sec 5	sec 6	sec 7	sec 8	sec 9	sec 10	sec 11	sec 12	Average
Measured	1.47	2.08	1.76	1.91	1.96	1.93	1.81	1.70	1.23	2.23	2.03	2.25	1.72
Linear regression	2.01	1.92	2.59	2.24	2.90	2.30	2.26	2.63	1.93	1.94	2.28	2.07	1.90
Joint probability	1.15	1.98	1.58	1.83	2.06	2.09	1.62	1.66	1.51	2.16	1.80	2.18	1.73

Susan

Sector Method	sec 1	sec 2	sec 3	sec 4	sec 5	sec 6	sec 7	sec 8	sec 9	sec 10	sec 11	sec 12	Average
Measured	1.83	2.81	2.54	1.44	1.31	1.38	1.83	2.55	2.20	2.16	2.24	2.44	1.98
Linear regression	2.69	2.20	2.48	2.65	1.85	2.35	1.97	2.44	2.39	3.67	3.27	2.79	2.38
Joint probability	1.87	2.70	2.53	1.91	1.50	1.60	2.18	3.21	2.22	2.34	2.23	2.32	2.11

Figure E.2 Directional Weibull parameter k of each site