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An Automated Decision-Making Approach for Assortment of Wind Turbines – A Case Study of Turbines in the Range of 500 KW to 750 KW

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Abstract: Wind energy has emerged as an important field of study in today's era. A fundamental aspect of this study is the efficient design of wind farms. This design process considers a number of conflicting design criteria. Therefore, a solution is desired that provides the best balance between all design criteria. In this paper, an automated decision-making approach based fuzzy logic is proposed to address the multi-criteria aspects of the problem under consideration. This problem requires finding the optimum balance between two important design criteria, namely, hub height and rated output percentage. By utilizing the Unified And-Or (UAO) fuzzy aggregation operator, a mechanism is developed to achieve the best tradeoff between the two design criteria. The proposed approach is applied to data collected from a real location. Results reveal the effectiveness of the proposed approach in addressing the issue of finding the optimal combination values for the hub height and rated output percentage.

Keywords: Wind turbine, Automated decision-making, Fuzzy logic, Wind energy

1. INTRODUCTION

In today's society, necessary and fundamental requirements for survival demand continuous supply of electricity. However, it is not always possible to provide grid connected electricity everywhere and any time with the present infrastructure. A possible answer to satisfy this deficiency in energy supply is utilization of off-grid and isolated power systems based on renewable sources of energy. Such sources include wind, solar photovoltaic and solar thermal, geothermal, biogas, tidal, wave, etc. which are available almost everywhere; on land or off-shore. [1]

Currently, use of wind energy is getting global encouragement for energy generation due to its commercial acceptability and economical compatibility compared with traditional sources of energy. The key advantage of using wind energy is due to its environmental friendliness, free availability, and reliability. This advantage is further augmented by is quick infrastructure development and deployment, negligible maintenance, and is utilized without any political or geographical boundaries [1]. According to Global Wind Energy Council Report [2], the world's wind power capacity grew by 44 % in 2014 with addition of 51,477 MW to bring total installations to 369,553 MW.

Despite the fact that extraction of wind power is easy, it is challenging to manage its quality and throughput caused by intermittent and fluctuating nature of wind speed. Various factors, such as time, location, and height above ground level (AGL) have a substantial contribution to the variation in wind speed. Usually, wind speed measurements are taken at 10 meters AGL while the rotor of the wind turbines rests at a much higher altitude on towers (also known as hub). Hub height denotes the height of the tower on which rotor of the turbine is mounted so that wind power can be absorbed and then converted into electrical energy. The hub height cannot exceed a threshold due to economical, installation, and maintenance issues and limitations. Thus, precise knowledge of optimal or near optimal hub height, which can produce maximum energy at an affordable cost, convenience in installation and maintenance is essential for the placement of wind turbines. In order to address the concerns related to quality of wind power, the rated energy output of the wind turbine should be maximized. This indicates that hub height and energy output are conflicting in nature since wind power is stronger at higher hub heights. Therefore, improvement in one criterion cannot be

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achieved without degradation of the other. Therefore, it is not possible to find the optimal value of each criteria individually. The only alternative method is to find the best balance between the two criteria, such that the best possible value of each criteria is found. This paper addresses this issue through use of multi-criteria decision-making (MCDM) using fuzzy logic. [1]

The rest of this paper is organized as follows. Section 2 provides the details on multi-criteria aspects of wind turbine assortment problem. A fuzzy logic based approach for wind farm assortment is discussed in Section 3. This is followed by results and discussion in Section 4. Finally, the conclusion is given in Section 5.

2. MULTI-CRITERIA ASPECTS OF WIND TURBINE ASSORTMENT

The design phase of the wind farm deals with various issues. One major concern is related to the design criteria used in the design process. From a technical perspective, installation of wind turbine in a wind farm is a critical task which is due transportation, installation, and maintenance costs of the mounting tower and turbine. Thus, one objective in the design phase is to minimize this overall cost. The cost of hub tower is an significant factor that contributes to the overall cost. Hub height has a considerable impact on the cost of a turbine. An increase by only 10 meters in the hub height results in cost increment in the range of 6% to 16%, with an average increase of 10.33%. Therefore, it is necessary to keep this height as low as possible.

On the other hand, when it comes to the operator of the wind farm, another essential requirement is the maximization of the power generated by the wind farm. This power generation is affected by a several factors such as electrical losses, wake effect losses, unavailability losses, rated output percentage (RPO), and zero output percentage (ZPO). Rated output percentage is defined as the duration of time during the year for which the wind turbine output was at its maximum rated capacity. RPO has a positive effect on the overall power generation, and therefore should be maximized as much as possible, to maximize the generated power.

It should be noted in technical sense that increasing hub height should also increase RPO, since at a higher altitude, more wind is available. This enhances the absorption of more wind by a turbine, resulting in more conversion of wind energy into electrical energy. However, as mentioned earlier, higher hub is difficult to manage due to technical and financial reasons. Therefore, it is not possible to have hub height and RPO optimized simultaneously. The adopted approach in this situation is to find the best tradeoff between the two criteria, such that both criteria would be satisfied to the best possible extent. This can conveniently be handled with multiple criteria decision-making (MCDM) using fuzzy logic, as explained in the following section.

3. FUZZY LOGIC APPROACH TO WIND FARM ASSORTMENT

Multiple criteria decision making (MCDM) is a technique used in scenarios where decisions need to be made in presence of multiple and conflicting criteria [3]. MCDM is concerned with decisions about selecting the best alternative from a finite set of available alternatives. The presence of multiple criteria triggers a number of issues involved with MCDM. In majority of problems, the data associated with criteria are non-commensurate. Furthermore, the preference of criteria over one another is often desired by the decision maker. A number of approaches exist to deal with these two issues, and fuzzy logic [4] has been effectively used to solve a number of MCDM problems involving these issues [3][5-13].

Another important reason to consider fuzzy logic for MCDM problems is the approach fuzzy logic handles uncertainties in design data. Although it is possible to describe uncertainties in terms of conditional probabilities, it is difficult in the majority of practical cases [14]. A framework for representing such knowledge is easily provided by fuzzy logic.

Application of fuzzy logic to MCDM problems require that the criteria are combined to form an overall decision function in for of a scalar value. A concern is the selection of an appropriate function, since there are wide variety of fuzzy functions available. Usually, the objective in MCDM problems is to satisfy all criteria simultaneously, resulting in the "pure ANDing" operation. However, the pure ANDing operation was originally represented as the "Min" function, as defined by Zadeh [15]. In mathematical terms, this representation is very rigid, since it only considers the effect of the lower quality criteria, while completely ignoring the positive effect of the higher quality criteria. To overcome this limitation, the fuzzy AND function has been redefined by many researchers with various mathematical representations such as Hamacher operator, Werners operator, Einstein operator, Weber operators, among many others. One such redefinition emerged in the form of Unified And-Or (UAO) operator [16]. A detailed discussion and mathematical properties of the operator can be found in [16].

A. *Unified And-Or Operator for the underlying problem*

To employ the UAO operator for the proposed problem, two linguistic variables, namely, "Hub Height" and "Rated Output Percentage" are defined. Our interest is in the terms "low hub height" and "high rated output". Since the two criteria are in mutual conflict, the objective is to find the optimal ratio that provides the best balance between the hub height and rated output percentage. For this purpose, the following fuzzy rule is defined.

Rule 1: IF a combination X has low hub height AND high rated output THEN it is a good combination.

In the above rule, X refers to a combination that has resulted due to a certain value of hub height and its corresponding rated output. The terms “low hub height”, “high rated output”, and “good combination” are linguistic values, each of which defines a fuzzy subset of solutions. For example, low hub height is the fuzzy subset of solutions of low hub heights. Each fuzzy subset is defined by a membership function μ. The membership function returns a value in the interval [0,1] which describes the degree of satisfaction with the decision criterion under consideration. Rule 1 can be mathematically represented using the UAO operator as follows:

$$\mu(x)^{I_\star} = \frac{\prod_{i=1}^{2} \mu_i(x) + \nu \max\{\mu_1(x), \mu_2(x)\}}{\nu + \max\{\mu_1(x), \mu_2(x)\}} \tag{1}$$

where $\mu(x)$ is the membership value for combination x in the fuzzy set *good combination*. Furthermore, $\mu_i(x)$ for $i = \{1,2\}$ denotes the membership values of combination x in the fuzzy sets *low hub height* and *high rated output* respectively. The solution which results in the maximum value for (2) is reported as the best solution found.

The membership functions for the two criteria are found as follows:

B. Membership function for hub height

The formation of membership function for hub height requires the upper and lower limits for hub height to be determined. In real wind farm designs, the hub height is generally taken between 40 m and 120 m. Therefore, the lower limit, “HMin” is defined as 30m while upper limit, “HMax” is defined as 120m. The corresponding membership function is illustrated in Figure 1, where the *x-axis* represents the hub height and the *y-axis* represents the membership value.

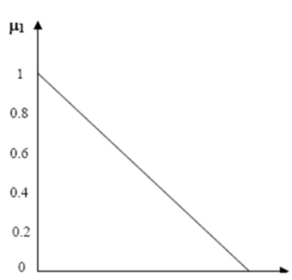

Figure 1. Membership function for hub height

C. Membership function for rated output percentage

The membership function for the rated output criterion can be determined following the same approach used for the membership function of hub height. The upper and lower limits for rated output need to be defined. From the available data, it is observed that the rated output varies between 0.02% and 9.71%. Therefore, to accommodate this range, the lower limit, “RMin”, is taken as 0.0% whereas the upper limit, “RMax”, is defined as 10%. The corresponding membership function is shown in Figure 2, *x-axis* represents the rated output percentage and the *y-axis* represents the membership value.

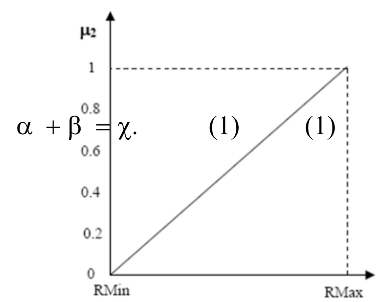

Figure 2. Membership function for rated output percentage

4. RESULTS AND DISCUSSION

The study was done on a potential experimental site near the eastern part of Saudi Arabia. The location had an altitude of 3 meters above sea level. The data for the study was collected from October 1995 to November 2000. The collected data was first filtered and relevant useful information was extracted. The required information was basically the rated output percentage measured with a step size of 5 meters. The data was then submitted to the developed program which performed the multi-criteria decision-making calculations and provided the fuzzified output. For each set of data pertaining to a specific turbine, the value which generated the highest fuzzified value was chosen as the best tradeoff solution. Four different turbine types with rated power of 500KW to 750KW were used in the study. Technical specifications of these turbines are listed in Table 1.

TABLE I. TECHNICAL SPECFICATIONS OF THE WIND TURBINES

Turbine	Rotor Diamter (m)	Cut-in Wind Speed (m/s)	Rated Wind Speed (m/s)	Rated Power (kW)
Fuhrlder FL600	50	2.5	11	600
Hyosung HS50	50	3.5	11	750
Unison U57	57	3	10.5	750
Windlfow 500	33	6	14	500

Tables II to V exhibit the results for the four turbines used in the study. In each table, columns 1 and 2 provide the Hub Height and percentage of Rated Output, respectively. Columns 3 and 4 enlist the individual membership values for the two criteria as μ_{HH} for Hub Height, and μ_{RO} for Rated Output percentage, respectively. The overall membership value which is calculated through aggregation using the UAO operator (denoted by UAO), is given in the last column of each table. It should be noted from these tables that the measurements of RO percentage were taken starting from a minimum hub height applicable to that turbine and relative to the rotor diameter. For example, there are two turbines whose rotor diameter was 50 meters (refer to diameters of Fuhrlder FL 600 and Hyosung HS50 in Table I). Therefore, for these two turbines, a measurements were taken starting with hub height of at least 55 meters. Following the same approach, minimum hub height for Unison U57 was 60 meters and for Window 500 was 40 meters.

It is observed from Tables II to V that for all turbines, the best overall membership values (given in boldface in the tables) are associated with the lowest hub height applicable to that turbine. This indicates that at low hub heights, the performance of a specific turbine in terms of RO percentage is better than those at high hub heights.

TABLE II. RESULTS FOR FUHRLDER 600. HH = HUBHEIGHT, RO = RATED OUTPUT, μ_{HH} = HH MEMBERSHIP, μ_{RO} = RO MEMBERSHIP, UAO = OVERALL MEMBERSHIP USING UAO OPERATOR. BEST OVERALL MEMBERSHIP IS IN BOLD.

HH	RO	μ_{HH}	μ_{RO}	UAO
55	3.31	0.722	0.331	**0.4910**
60	3.52	0.667	0.352	0.4869
65	3.77	0.611	0.377	0.4824
70	3.99	0.556	0.399	0.4732
75	4.27	0.500	0.427	0.4635
80	4.54	0.444	0.454	0.4495
85	4.84	0.389	0.484	0.4372
90	5.16	0.333	0.516	0.4232
95	5.52	0.278	0.552	0.4081
100	5.92	0.222	0.592	0.3915
105	6.32	0.167	0.632	0.3722
110	6.79	0.111	0.679	0.3519
115	7.29	0.056	0.729	0.3295
120	7.78	0.000	0.778	0.3044

TABLE III. RESULTS FOR HYOSUNG HS 50. HH = HUBHEIGHT, RO = RATED OUTPUT, μ_{HH} = HH MEMBERSHIP, μ_{RO} = RO MEMBERSHIP, UAO = OVERALL MEMBERSHIP USING UAO OPERATOR. BEST OVERALL MEMBERSHIP IS IN BOLD.

HH	RO	μ_{HH}	μ_{RO}	UAO
55	0.2	0.722	0.020	**0.3073**
60	0.23	0.667	0.023	0.2989
65	0.27	0.611	0.027	0.2899
70	0.3	0.556	0.030	0.2789
75	0.34	0.500	0.034	0.2670
80	0.37	0.444	0.037	0.2527
85	0.41	0.389	0.041	0.2367
90	0.45	0.333	0.045	0.2180
95	0.5	0.278	0.050	0.1964
100	0.55	0.222	0.055	0.1708
105	0.62	0.167	0.062	0.1405
110	0.67	0.111	0.067	0.1031
115	0.73	0.056	0.073	0.0708
120	0.8	0.000	0.080	0.0690

TABLE IV. RESULTS FOR UNISON U57. HH = HUBHEIGHT, RO = RATED OUTPUT, μ_{HH} = HH MEMBERSHIP, μ_{RO} = RO MEMBERSHIP, UAO = OVERALL MEMBERSHIP USING UAO OPERATOR. BEST OVERALL MEMBERSHIP IS IN BOLD.

HH	RO	μ_{HH}	μ_{RO}	UAO
60	4.38	0.667	0.438	**0.5360**
65	4.67	0.611	0.467	0.5319
70	4.98	0.556	0.498	0.5253
75	5.31	0.500	0.531	0.5150
80	5.69	0.444	0.569	0.5027
85	6.05	0.389	0.605	0.4867

90	6.49	0.333	0.649	0.4707
95	6.96	0.278	0.696	0.4526
100	7.46	0.222	0.746	0.4324
105	8	0.167	0.800	0.4103
110	8.54	0.111	0.854	0.3854
115	9.12	0.056	0.912	0.3588
120	9.71	0.000	0.971	0.3300

TABLE V. RESULTS FOR UNISON U57. HH = HUBHEIGHT, RO = RATED OUTPUT, μ_{HH} = HH MEMBERSHIP, μ_{RO} = RO MEMBERSHIP, UAO = OVERALL MEMBERSHIP USING UAO OPERATOR. BEST OVERALL MEMBERSHIP IS IN BOLD.

HH	RO	μ_{HH}	μ_{RO}	UAO
40	0.21	0.889	0.021	**0.3334**
45	0.25	0.833	0.025	0.3281
50	0.3	0.778	0.030	0.3226
55	0.34	0.722	0.034	0.3155
60	0.39	0.667	0.039	0.3080
65	0.43	0.611	0.043	0.2987
70	0.49	0.556	0.049	0.2889
75	0.54	0.500	0.054	0.2770
80	0.59	0.444	0.059	0.2631
85	0.65	0.389	0.065	0.2472
90	0.72	0.333	0.072	0.2288
95	0.78	0.278	0.078	0.2064
100	0.84	0.222	0.084	0.1797
105	0.91	0.167	0.091	0.1478
110	1	0.111	0.100	0.1091
115	1.07	0.056	0.107	0.0979
120	1.18	0.000	0.118	0.0955

TABLE VI. TECHNICAL SPECFICATIONS OF THE WIND TURBINES

Turbine	Rated power	HH	RO	μ_{HH}	μ_{RO}	UAO
Fuhrlder FL600	600	55	3.31	0.722	0.331	0.4910
Hyosung HS50	750	55	0.20	0.722	0.020	0.3073
Unison U57	750	60	4.38	0.667	0.438	0.5360
Windflow 500	500	40	0.21	0.889	0.021	0.3334

In addition to the above analysis, the study also evaluated the relative performance of the wind turbines. Table VI provides the best results for each turbine. These results have been reproduced from Tables II to V for convenience. It is observed from these tables that among all turbines, Unison U57 demonstrated the best performance, since it was able to achieve the best balance between the hub height and RO percentage, as indicated by its UAO value of 0.5360. The nearest competitor to Unison U57 was Fuhrlder FL 600 which had a UAO value of 0.4910. The remaining two turbines were far away from the above two turbines since those turbines had UAO values ranging between 0.3073 for Hyosung HS50 and 0.3334 for Window 500. Therefore, based on the above results, Unison U57 or Fuhrlder FL 600 can be recommended for deployment at the test site under study.

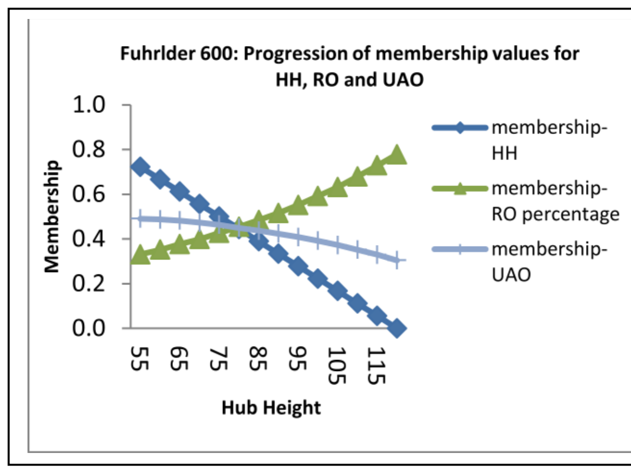

Figure 3. Membership plots for HH, RO, and UAO – Fuhrlder FL 600

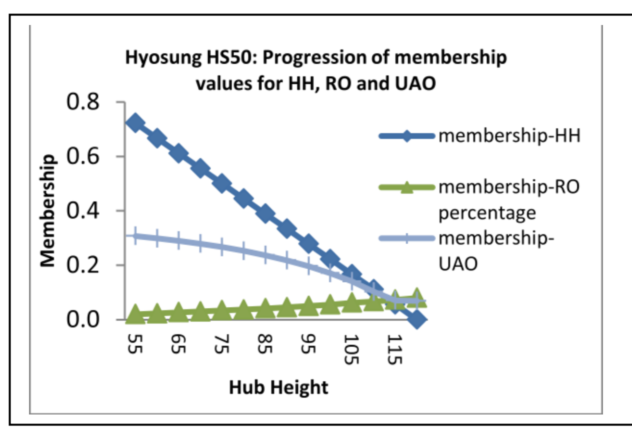

Figure 4. Membership plots for HH, RO, and UAO Hyosung HS 50

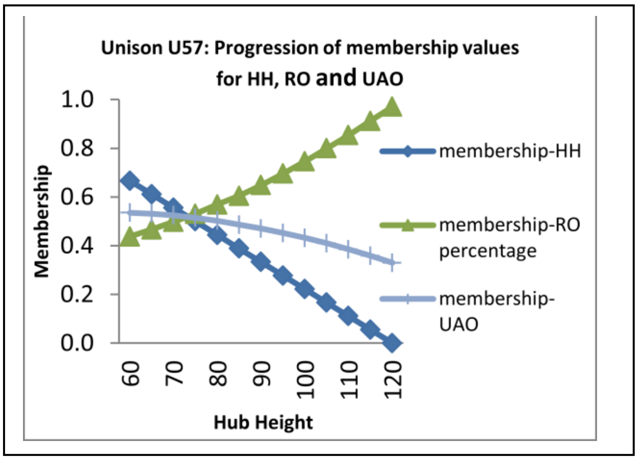

Figure 5. Membership plots for HH, RO, and UAO - Unison U57

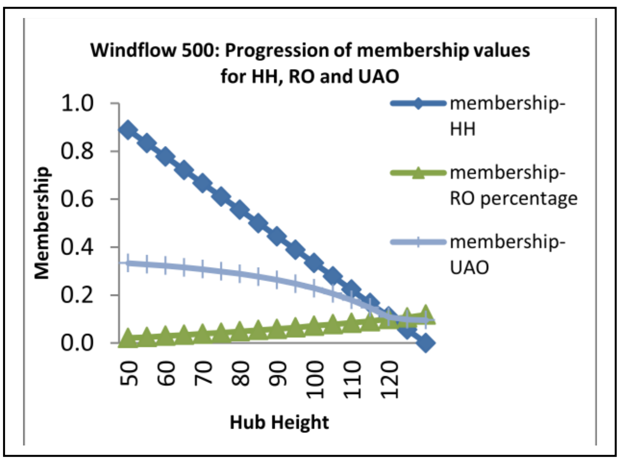

Figure 6. Membership plots for HH, RO, and UAO

Windflow 500

Figures 3 to 6 display the behavior of the overall membership (UAO), as well as that of µHH and µRO for each turbine. The figures show that the UAO values are affected more by µRO than µHH the for Hyosung HS50 and Window 500. In contrast, for Fuhrdler 600 and Unison U57, both µHH and µRO have somewhat a more balanced impact on overall membership (UAO).

5. CONCLUSION

In the process of wind farm design, an important issue for a specific site is the selection of most suitable turbine out of many choices. Two factors that have a considerable impact on this selection is the Hub Height and Rated Output percentage. These important parameters have vital role in the decision making process. This paper has presented an automated approach based on fuzzy logic to find the most appropriate balance of the two criteria, using real data collected from a real location. The two criteria were aggregated into a scalar function using Unified And-Or fuzzy operator. The effectiveness of the approach was tested through application on various turbines in rated output range of 500 KW to 750 KW. Results revealed that Unison U57 showed the best performance, with Fuhrlder FL 600 being a strong alternative. Another interesting finding from the study was that for rated power considered, the best balance between the hub height and percentage of rated power output was found when the lowest hub height for that particular turbines was considered, as evident from the UAO values.

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