Reduction of uncertainty in resource assessment through wind flow model "ensemble"

Rui Pereira[1], Ricardo Guedes[1], Silva Santos[1,2]

[1] MEGAJOULE Inovação, Lda
Rua Eng. Frederico Ulrich, 2650 / 4470-605 Moreira da Maia - PORTUGAL
Phone: +351 220 915 480 …Email: rui.pereira@megajoule.pt / megajoule.inov@megajoule.pt
URL: www.megajoule.pt

[2] ISEP – Engineering Institute of OPorto

ABSTRACT: When estimating wind farm energy yield, the numerical modelling of wind flow is responsible for a great share of the results uncertainty.

Industry has relied on linear flow models, namely WAsP, throughout the last 20 years but CFD models application is rising.

Although CFD models are, in principle, able to provide more accurate results, higher user expertise relatively short track record still lead to some mistrust within the industry.

The authors believe that WAsP and CFD models should not be regarded as alternatives to each other, but rather as associates. Based on the fact that WAsP and CFD share very different modelling principles, the smart association, or "ensemble", of CFD and WAsP estimates can actually lead to a lower uncertainty than any individual result.

Since errors in CFD and WAsP model results are, at least, partially, uncorrelated, individual results can be combined in an optimal manner (by means of a weighted average or similar) to give minimum uncertainty levels.

The authors have addressed the correlation between WAsP and CFD errors for a set of nearly 20 test cases. The evidence was that, for those, WAsP and CFD errors were uncorrelated.

The algebra of estimate "ensemble" and uncertainty calculation is presented and discussed.

The "ensemble" principle was tested for all study cases. Results show that the optimum "ensemble" is more probable to lead to better estimates than each individual result.

The number and diversity of cases is still limited for these conclusions to be extrapolated. Moreover, only average wind speed estimates were considered. Frequency wind rose, wind speed histogram and wind turbine output must also be addressed. Sensitivity to inputs and model setup options should also be considered.

Keywords: Optimization, Uncertainty, Complex terrain, CFD, Cross predictions

1. Introduction

Numerical modelling of wind conditions, is responsible for a significant share of the uncertainty on a wind farm energy yield estiamte.

For the last 20 years, numerical modelling of surface wind for wind energy applications has been dominated by linear models, namely WAsP. Although initially developed for flat terrain, WAsP proved useful also for complex terrain sites, since some application principles are still guaranteed (namely the Similarity Principle) [1,2,3]. WAsP's long track record gives the industry a great degree of comfort and acceptance.

In the last 5 to 10 years, the so called Computational Fluid Dynamics (CFD) models have been gaining relevance within the wind industry. Firstly, because CFD can model the full wind flow field, unlike WAsP, and secondly, because they can capture, accurately or not, the flow complexity induced by terrain or obstacles.

A lot of debate has been generated around the relative performance of CFD and WAsP during the last years. However, the improvement in resource assessment accuracy (average stationary yearly wind statistics) with CFD is not yet clearly proven.

The authors believe that, based on the fact that WAsP and CFDs share very different modelling principles, the combination, or "ensemble", of CFD and WAsP estimates can actually lead to a reduction of uncertainty levels.

The "ensemble" approach is very common in meteorological forecasts and is nowadays common in forecasting wind farm production.

The usefulness of the "ensemble" of estimates will depend mainly on the degree of independence between WAsP and CFD errors, and the optimization of the "ensemble" estimate.

The "ensemble" of individual estimates can be achieved by the application of a portfolio theory, following the *Modern Portfolio Theory* by Markowitz. The optimum combination of estimates, which minimizes uncertainty, can also be found.

This paper describes a possible approach to the optimal "ensemble" of average wind speed estimates from CFD and WAsP.

At this stage, the "ensemble" model is only defined for single average wind speed.

By the use of 7 different case studies, the evidence of uncorrelation between WAsP and CFD prediction errors is also assessed.

Finally, some example cases are presented, for illustrative reasons.

The authors intend to further develop this methodology so as to be applicable to more than simply average wind speed values and to further confirm the independence between WAsP and CFD results.

2. Description of concept

2.1. "Ensemble" of average wind speed estimates

A simple "ensemble" model can be considered to calculate a combined estimate for average annual wind speed.

Consider that:

> V_A and V_B are the average wind speed estimates from 2 different wind flow models (A and B);
>
> U_A and U_B are the wind flow model uncertainties in the above estimates

A simple "ensemble" of estimates can be described as:

$$V_{A+B} = V_A W_A + V_B W_B$$

$$W_A + W_B = 1$$

where W_A and W_B are the weights for A and B estimates, respectively.

The Uncertainty of the "ensemble" estimate, U_{A+B} will have the following expression [4].:

$$U_{A+B} = \sqrt{(U_A W_A)^2 + (U_B W_B)^2 + 2\rho_{AB} U_A W_A U_B W_B}$$

where ρ_{AB} is the covariance between V_A and V_B.

The covariance can also be described by the correlation between V_A and V_B, or by the *Pearson* (R^2) coefficient. The covariance between V_A and V_B estimates represents then the degree of correlation, or dependence, that WAsP and CFD estimates have between each other.

From the above expression, if ρ = 1 then:

$$U_{A+B} = U_A W_A + U_B W_B$$

So, the "ensemble" uncertainty will be the equal to the weighted average of individual uncertainties. Thus, no advantage is gained with the "ensemble" of predictions as the best choice will be simply to select the estimate with lowest uncertainty to begin with.

However, if $\rho < 1$, then:

$$U_{A+B} < U_A W_A + U_B W_B$$

So, the uncertainty of the "ensemble" estimate can actually be lower than any individual uncertainty.

Therefore, the benefit of "ensemble" from WAsP's and CFD estimates will be deeply related with the amount of uncorrelation between both model uncertainties, or, in other words, the degree of independence between estimates.

2.2. Optimal "Ensemble"

In a resource assessment point of view, an optimal "ensemble" will be one which minimizes uncertainty of the "ensemble" estimate. From the expressions above, an optimal "ensemble" can be found by an optimal combination of weights.

This is the basis of any *Portfolio Theory* [5]. However, while optimizing a asset portfolio the optimization follows allways two criteria – maximum return for given risk or minimum risk for a given return – in this case we are only looking for minimum risk, or uncerrtainty.

The following figure illustrates the evolution of "ensemble" uncertainty U_{A+B} with weigth varitation, and also de point with minimum uncertainty, for a case were V_A and V_B are independent ($\rho = 0$).

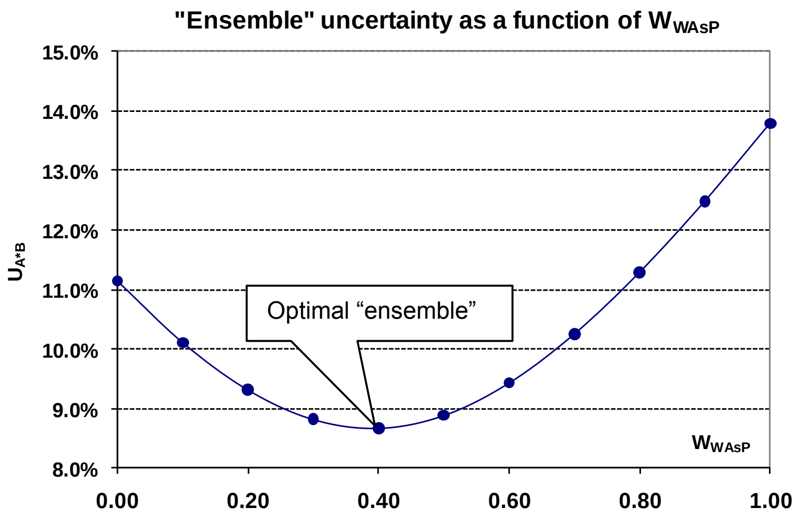

Figure 1 - Evolution of "ensemble" Uncertainty with weights and optimal "ensemble" (example for uncorrelated estimates)

The following *abacus* can be derived and represents the weights of the "ensemble" estimates that will minimize uncertainty, as a function of individual model uncertainties, also for a case were V_A and V_B are independent.

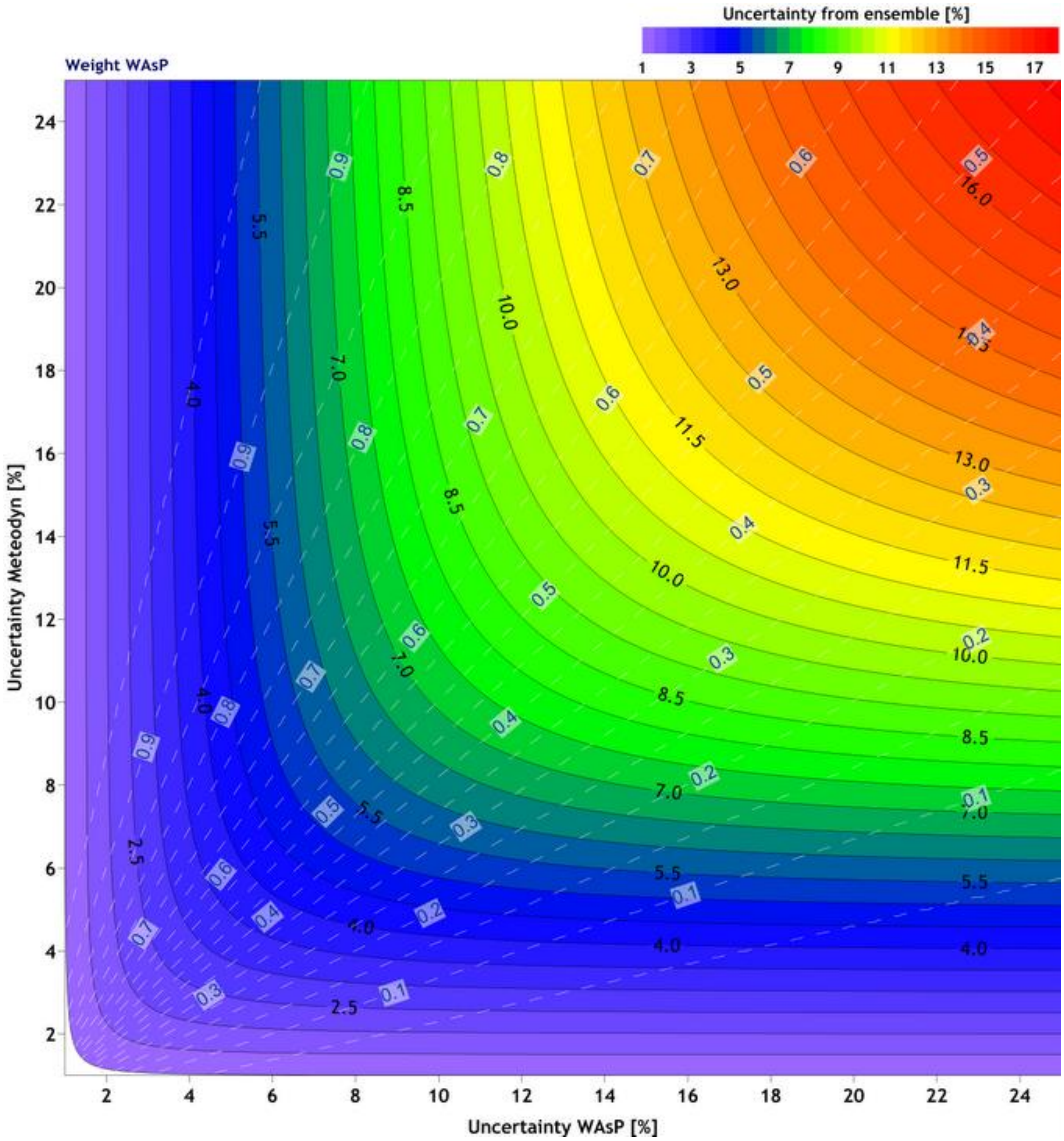

Figure 2 - Optimal "ensemble" for different Uncertainty combinations (example for uncorrelated estimates)

2.3. Limit to the "Ensemble" approach

Obviously, there will be a limit after which the "ensemble" approach will no longer be interesting - no combination of estimates will result in lower uncertainty.

This will be the case when one of the individual uncertainties is too low, when compared to the other. In those cases, the best estimate would simply be the one with the lowest uncertainty. This limit can be determined from the above expressions.

For a case where V_A and V_B are independent and U_A/U_B is approximately 9.9 or higher, then the optimal solution will be simply to consider V_B, the most accurate estimate.

For different covariance between V_A and V_B , ρ, different limits will apply.

3. Covariance between WAsP and CFD wind speed estimates

The most straightforward way to assess the covariance between WAsP and CFD estimates of average wind speed is to compare modelling errors for a set of similar test cases. To really assess independence of modelling process, the test cases should be exactly the same, input data should be equal and CFD setup should be the same in all cases.

For this purpose, the authors have gathered a sample of 7 test cases. For those sites, WAsP and CFD estimates at selected local mast sites were compared. The CFD code used was the commercial code MeteodynWT.

Sites are diverse in terms of location, wind climate and land cover, although all of them are typical mountainous sites with moderate to high terrain complexity.

Wind measurements campaigns were conducted on all sites and on most of them with more than one mast.

To prevent any bias on results and conclusions that could be caused by user interference, in each case, a standard approach to both WAsP and MeteodynWT models was defined.

Both models shared exactly the same inputs, in terms of digital elevation and roughness maps and input observed wind data.

More details about the test setup and results can be seen in reference [6].

The following picture compares the average wind speed estimate error for WAsP and CFD for exactly the same cases.

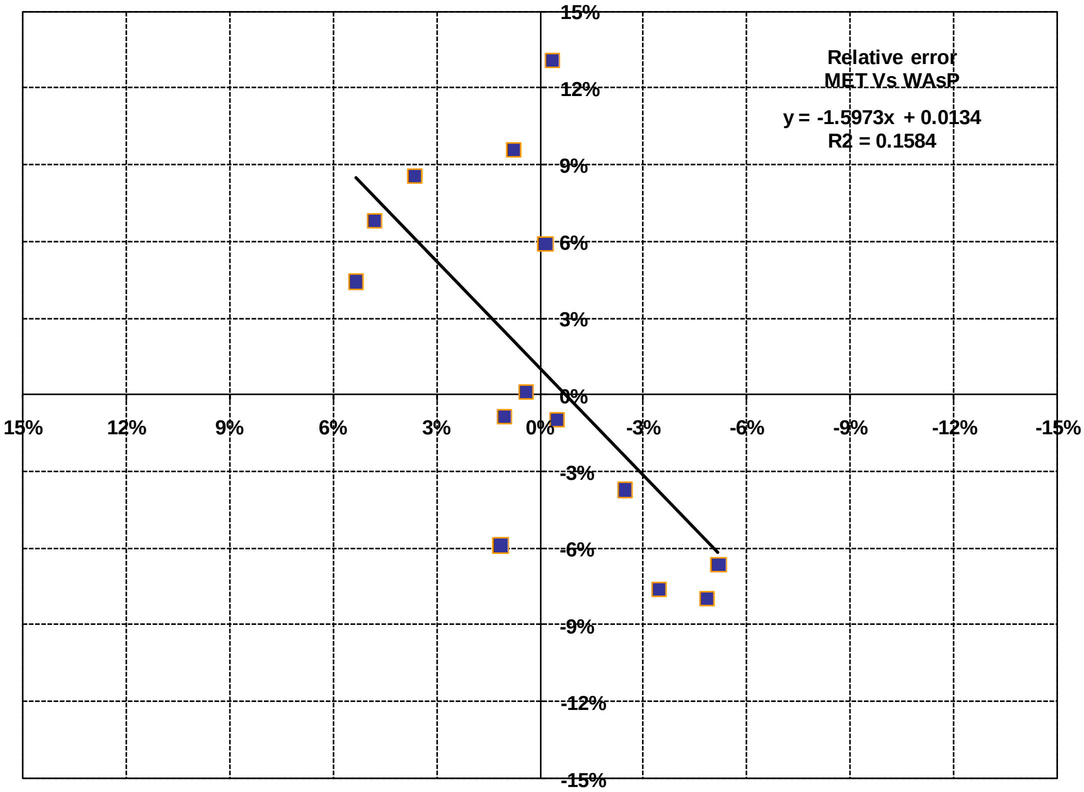

Figure 3 - Average wind speed estimate error for WAsP and CFD

It can be clearly seen that, in these cases, results from both models are uncorrelated. No relationship between errors in WAsP and CFD is found.

This result, in what regards “ensemble” estimates, is the most advantageous. As discussed in the previous section, with uncorrelated estimates the “ensemble” uncertainty will be at a minimum, when compared with the uncertainty from each individual estimate.

Naturally that this result should be confronted with other test cases and a general conclusion will only be valid for a greater set of sites. However, the indication that modelling results are independent from each other is in agreement with the difference in modelling principle of the two models.

It should also be remarked that the overall uncertainty on wind speed estimates is related to several features other than the wind flow modelling itself. Aspects as quality and representativeness of local wind measurements, wind turbine data, accuracy of the altitude and roughness digital maps, etc., will be all relevant sources of uncertainty and, most likely, will be present in any modelling approach when .

This paper only focus on the uncertainty on the wind flow modelling itself, leaving aside uncertainty on inputs and adjustments or calculations on outputs.

4. Examples of “Ensemble” of model estimates

To better illustrate the application and potential benefits of “ensemble” of resource assessment estimates, a set of very simple examples are devised.

For that purpose consider the scenarios in the following table. These scenarios are derived from the same tests used to assess the correlation in the previous section [6].

In these tests, predictions were made for sites with observations from both WasP and the CFD model.

Table 1 – Observation of the average annual wind speed and estimates for WAsP and CFD

[m/s]	A1	A2	B1	B2	C1	C2	D1	D2	E1	E2	F1	F2	G1	G2
Observations	6.46	6.95	8.12	6.57	6.55	7.34	7.66	7.54	5.50	5.81	6.29	6.27	7.26	7.94
WAsP estimates	6.84	6.54	8.04	7.20	6.84	6.85	7.05	8.05	6.22	5.76	6.83	5.79	7.27	7.64
Meteodyn estimates	6.45	7.03	8.08	6.62	6.90	6.96	7.29	7.90	5.48	5.87	6.52	6.05	7.29	7.74

Obviously that uncertainty on these estimates is case dependent and would have to be addressed in regards to each particular site conditions. The assumed uncertainty figures are also difficult to achieve and always subject to argument and dispute, namely for CFD estimates for which there is a smaller track record and references.

As the purpose of this paper is mainly illustrative, a more pragmatic approach will serve the authors intent. Thus, the uncertainty for each model estimate was considered equal for all sites. The values were taken simply as the RMS (Root Mean Square) of all estimates their respective estimates (scenario i: WAsP = 6.8%; CFD = 3.1%) or as the RMS plus one standard deviation (scenario ii: WasP = 13.8%; CFD = 6.4%) [6].

Also for illustrative purposes, Case C1 average wind speeds are considered.

The following tables compare, for each uncertainty scenario, the combined estimate and uncertainty that could be calculated for an average estimate (W_{CFD}=W_{WAsP}=0.5) and for an optimal “ensemble”.

The “ensemble” assumed uncorrelation between WAsP and CFD, as discussed in the previous section (ρ = 0). The optimal “ensemble” would have the major weigth for the CFD estimate (W_{CFD}=0.83 and W_{WAsP}=0.17).

Table 2 – Uncertainty scenarios with a simple average (W_A and W_B equal to 0.5) for case C2

	WAsP	CFD	Average	Optimal "ensemble”
V [m/s]	*6.85*	*7.34*	*7.09*	***7.26***
U	13.8%	6.4%	7.7%	**5.8%**

As it can be seen, when compared with the most accurate estimate (CFD), the “ensemble” estimate represents a reduction of 0.6 percent points in uncertainty. The reduction for a simple average result is of 1.9 percent points.

The optimization method can be easily implemented in regular spreadsheets with use of iterative methods [7].

The uncertainty dependence on the combination of estimates can be drawn, for any case. The evolution of uncertainties as a function of WAsP weights are shown in the figure below.

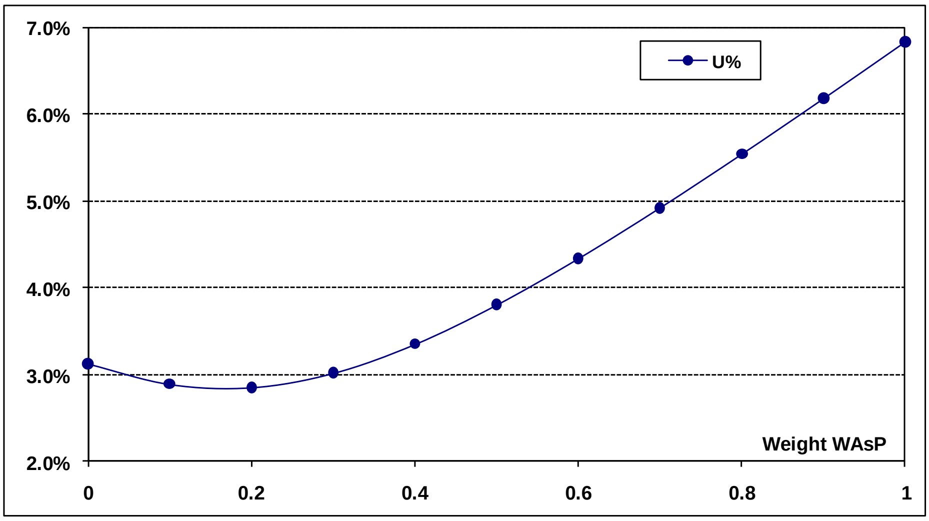

Figure 4 - Evolution of “ensemble” Uncertainty with weights for presented case

5. Final Remarks

An “ensemble” technique was proposed with the aim of minimize the uncertainty associated at wind speed, estimated from two different wind flow models, WAsP and CFD.

This technique allows the simultaneous use of two wind flows models, WAsP and CFD models, through of an estimate of optimum weight for each models.

It possible to have “ensemble” of annual average wind speed estimates from different wind flow models, like WAsP and CFD models.

The benefit of the “ensemble” will be related to the level of independence on modelling results and the difference in individual model uncertainties

It’s possible, and easy, to find the optimum combination of individual estimates which will minimize “ensemble” uncertainty, through the application of an optimization method that finds the minimum of a scalar function of several variables, starting at an initial estimate.

For a case where V_A and V_B are independent the “ensemble” benefit should be limited to a ratio of U_A/U_B of approximately 9.9 or higher. In these cases, the optimal solution will be simply to consider V_B, the most accurate estimate.

The application of resource assessment “ensemble” should be developed, in order to provide a practical solution to wind farm energy estimates.

The level of uncorrelation between WAsP and other (CFD) models should be further assessed, as this is the most important assumption for the “ensemble” approach and number of tests should be increased to keep the uncorrelation levels.

In the future the authors hope increase the number of case tests and integrate several restrictions to improve the accuracy of proposed technique of “ensemble”.

6. References

[1] Anthony Bowen and Niels Mortensen, "Exploring the Limits of WASP – The Wind Atlas Analysis and Application Program". European Wind Energy Conference and Exhibition, 1996, Goteborg, Sweden.

[2] N. Mortensen, L. Landberg, I. Troen, Erik Petersen. Wind Atlas Analysis Program (WASP), 1993.

[3] Niels Mortensen and Erik Petersen, "Influence of Topographical Input Data on the Accuracy of Wind Flow Modelling in Complex Terrain". European Wind Energy Conference & Exhibition, 1997, Dublin, Ireland.

[4] ISO/IEC Guide 98:1995: Guide to the expression of uncertainty in measurement (GUM)

[5] Harry M. Markowitz, "Portfolio selection: efficient diversification of investments", 1991

[6] Rui Pereira, Ricardo Guedes, Carlos Santos - Megajoule Inovação, "Comparing WAsP and CFD wind resource estimates for the "regular" user" EWEC 2010

[7] Lagarias, J.C., J. A. Reeds, M. H. Wright, and P. E. Wright, "Convergence Properties of the Nelder-Mead Simplex Method in Low Dimensions," SIAM Journal of Optimization, Vol. 9 Number 1, pp. 112-147, 199