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Theory and User Manual BLADOPT

Energy Research Centre of the Netherlands ECN

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***Stork Product Engineering**

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Contents

Introduction

This document serves as the theory and user's manual of the computer program **BLADOPT** 1.0. The computer program **BLADOPT** is the successor of the **PVOPT**-1 program. The **BLADOPT** program is a numerical optimisation computer program to design rotor blades for Horizontal Axis Wind Turbines. The program is able to vary the rotor design parameters like the chord and twist distributions in such a way that the cost of energy is minimised. Other parameters that can also be optimised are rotor diameter, rotor speed and the rated power, although not more than 10 parameters can be optimised at the same time.

The main difference, for the user, with the program **PVOPT** is that the optimisation objective is not optimum energy yield but lowest cost of energy. This implies that not only the energy yield is predicted but also the cost of the wind turbine components and the operation and maintenance costs are determined. For all necessary cost items a user supplied value or a cost function is implemented. Due to the multidisciplinary models, aerodynamic and cost/engineering models in the program the **BLADOPT** code can be categorised as a Multidisciplinary Design Optimisation program.

In this manual a short description can be found of the optimisation schemes, the wind turbine model consisting of a description of the aerodynamic model, the cost functions, the noise model and the economic analysis. The user manual part contains a section on the installation of the program and the user interface.

Wind Turbine Optimisation

Introduction

In [1], the optimisation strategy for the **BLADOPT** program is selected.

To perform a multidisciplinary optimisation task a number of subjects have to be dealt with. For wind turbine design optimisation the following subjects have to be addressed:

- the objective and (boundary) conditions and constraint for the design parameters have to be defined;
- the aero-elastic code to predict the energy yield and the design load spectrum;
- the cost of the wind turbine, determined per component, based on design parameters and or response parameters like design loads, have to be determined;
- the optimisation algorithm.

In the specification of **BLADOPT** the recommendation for improvement of the **PVOPT** program [2] are taken into account.

The objective for the **BLADOPT** program is the lowest **C**ost **o**f **E**nergy (COE). To calculate the cost of energy it is necessary to calculate the energy yield, the investment cost for the turbine and the operation and maintenance cost. Together with some economic parameters like interest rate and economic lifetime it is then possible to determine the cost per kWh electricity generated. The design parameters that can be optimised with BLADOPT are the chord and twist distribution, the rotor diameter, the rotor speed and the rated power, although not all at the same time. Each parameter that be optimised should be constrained at the lower and upper side otherwise it might occur that the program ends up with a design that is not realisable. The design conditions are,

- the wind spectrum for the energy production and
- the wind distributions for the load spectrum.

To reduce the number of design parameters it is recommended to couple parameters in such a way that the optimisation process is fast and the results are in such a way that the designer does not need to smooth the results to come to a real product.

Due to the fact that function evaluations, i.e. determine the COE for a specific design, take quite some computational effort the optimisation strategy applied is such that the number of function evaluations is also assumed to be minimised.

Optimisation Strategy

A promising method found in literature, which is also used for other technologies, is a combination between a 0^{th} order conjugate direction method and a higher order optimisation method which uses an approximation of the *true* objective function. The main advantage of this method is that the 0^{th} order method

is capable to determine a better solution with a low number of design iterations and is probably less sensitive to non smooth object functions than the higher order optimisation algorithms.
The data obtained, in this phase, will be stored in a database to create a model approximating the *true* objective function. When this loop ends, due to the fact that one of the end criteria is/are met or sufficient data is the database to create an approximate model, the data in the database is used to construct a global approximation of the real objective function. Such an approximated objective function is less sensitive to all kinds of distortion, like numerical noise, which are present in the real objective function. A second optimisation algorithm based on a quadratic programming method is suitable to find the minimum of this function. A quadratic algorithm needs the Hessian matrix, whose components are the second partial derivatives of the objective function with all variables, which can easily be determined, especially because the derivatives can be determined analytically. Then the combination of design parameters that results in a local or the global minimum of the approximated objective function is evaluated with the real objective function.
As already mentioned before the number of parameters optimised in the **BLADOPT** program will be limited to 10 parameters, e.g. 3 to 5 radial stations for chord, 3 to 5 radial stations for twists, rotor diameter and tower height.
Future extensions of this program to **HATOPT**, a program by which the complete wind turbine can be optimised, motivated the decision to use the procedure as shown here.

The conjugate direction method of Powell, **COBYLA** [6,7], is used in the first n_{des}+1 function evaluations to get sufficient data to create sufficient data for the so-called response surface which is the approximation of the physical model.

In the following section some information is gathered with respect to approximated models and how to find the optimum for the approximated and real model.

To use the proposed procedure efficiently a strategy has to be determined which parameters to optimise first or which parameters have to be increased to a higher order in the approximation. This can best be evaluated by doing a sensitivity analysis per design variable to check the non-linearity of it with respect to the objective function.

Approximation Models

The reason for making an approximation of the real physical problem has been discussed in [1].
Approximation models can be classified as follows:

- a simplified engineering model (formal approximation) or
- a general approximation (generic approximation) e.g. based on a multidimensional polynomial curve or surface fitting.

Formal approximations are for the **BLADOPT** code not applicable since the wind and load prediction part is already very simplified version of the real problem. Generic approximations can easily be made for these problems.

Local Approximations

Local approximations are sufficiently accurate only in a limited region of the design space, namely in the vicinity of the point at which they are generated. Typically they are used to generate an approximate problem formulation that is solved for an optimum solution point. A new approximate formulation is then generated and solved until the process is sufficiently converged.

For building a generic approximation with Taylor series, first order only, around X_0,

$$g_L(x) = g(X_0) + \sum_{i=1}^{n} x_i - x_{oi} \left(\frac{\partial g}{\partial x_i} \right)_{X_0}$$

For some applications this approximation is not good enough, even near the design point X_0. Higher order expansions need however a fast increasing number of function evaluations. A way to get around this is the so-called reciprocal approximation, which is like the approximation above but with the reciprocal $1/x_i$. This is a commonly used method for structural programs where truss and plane stress elements are involved.

Global Approximations

The use of local approximations will soon need too many function evaluations. Global approximations, which are valid for the whole design space or large areas of it have at least the advantage that all function evaluations performed on a specific design will always be used to make an approximate model. Thus the approximate model can continuously become better although not necessarily so. The approximation model is usually made by polynomial curve or surface fitting based on the least square method.
Another advantage of this method is that it is possible to increase the weight of a specific or a large number of function evaluations. This could be applied e.g. on the last 1, … , n_{des} objective function evaluations. However one has to be careful applying the weighting especially when only a few function evaluations have been performed.

The approximation model chosen is an orthogonal polynomial of the form shown below for dimension 3 and order 3,

$$F(x_1, x_2, x_3, c_1, ..., c_m) =$$
$$c_1 + c_2x_1 + c_3x_2 + c_4x_3 + c_5x_1^2 + c_6x_1x_2 + c_7x_1x_3 + c_8x_2^2 + c_9x_2x_3 + c_{10}x_3^2 + c_{11}x_1^3 +$$
$$c_{12}x_1^2x_2 + c_{13}x_1^2x_3 + c_{14}x_1x_2^2 + c_{15}x_1x_2x_3 + c_{16}x_1x_3^2 + c_{17}x_2^3 + c_{18}x_2^2x_3 + c_{19}x_2x_3^2 + c_{20}x_3^3$$
$$= \sum_{i=1}^{m} c_i \psi_i (x_i, ..., x_3)$$

The increase in the minimum number of function evaluations, for a higher order approximation model, goes according to the relation below

$$\binom{n_{des} + order}{n_{des}} = \frac{(n_{des} + order)!}{n_{des}!\,order!}$$

The resulting number of function evaluations is shown in table 1. E.g. when the approximated model should be of 2nd order polynomial model for 7-design parameters at least 36 function evaluations are needed to construct such a multinomial.

Table 1 *the number of parameters to make a polynomial of an order d with n design parameters*

n_{des}	order				
	0	1	2	3	4
1	1	2	3	4	5
2	1	3	6	10	15
3	1	4	10	20	35
4	1	5	15	35	70
5	1	6	21	56	126
6	1	7	28	84	210
7	1	8	36	120	330

Usually it will not be necessary to optimise all 7-design parameters at a time. When the designer is interested to see what the sensitivity of one or more parameters is, the results of those function evaluations will be stored and can be used to update the approximated model.

The algorithm used to make such an approximation model is given in the ToMS (Transactions on Mathematical Software) database, see [5].

Each new function evaluation can be used to update and increase the reliability of the approximated objective function.

Finding the minimum of the approximation model

The minimum of the approximated model is found using a classical method taking the constraints into account. The method chosen is a Feasible Sequential Quadratic Programming (FSQP) algorithm, a super linear convergent algorithm for directly tackling optimisation problems, which can handle linear or non-linear inequality constraints and linear or non-linear equality constraints. The algorithm is described in [8].

Objective function

The objective function in **BLADOPT** is the Cost of Energy, calculated according to the simplified procedure described in the IEA Recommended Procedure, see [10]

$$LPC = I/(a \cdot AUE) + TOM/AUE$$

In which

I	Initial investment;
a	annuity factor, depending on discount rate and economic lifetime;
AUE	Annual utilised energy;
TOM	Total levelized annual "downline cost", i.e. Operations and maintenance, insurance, retrofit cost, and salvage cost.

This results in a yearly capital cost and operating and maintenance cost divided by the net energy production minus losses with in the wind farm. To determine the cost of energy it is necessary to determine a the following quantities:

- energy yield;
- total investment cost;
- operating and maintenance cost;
- economic parameters like interest and depreciation period.

The energy yield and total investment cost are determined by the wind turbine model and cost model while the operation and maintenance cost are a user supplied percentage of the total investment cost. The economic depreciation period and interest percentage are also parameters to be supplied by the user.

Wind Turbine Model

General description

The wind turbine model is simplified to a high extend. In fact, in the **BLADOPT** code the wind turbine consists of a rotor with a stiff blade on a stiff tower. The rotor is modelled as a single rotor blade at hub height, so wind shear or tower effect is not present.

The power control of the rotor can be

- constant speed (passive) stall;
- variable speed (active) stall;
- variable speed pitch to vane.

Variable speed control is constant λ control up to rated power or up to a certain maximum rotor speed supplied by the user. Variable speed control also influences the cost algorithm of the tower and vice versa. The tower cost algorithm determines the cheapest tower, which can have an eigenfrequency that is avoided by the control algorithm. This control is implemented through a second minimisation process with the following objective function

$$F = v_{tower}(\cos t) - v_{tower}(control)$$

Theory aerodynamic-load model

The aerodynamic model is based on the standard blade element momentum theory for axial induction factors < 0.38, or a turbulent wake expression for axial induction factors > 0.38. The calculations are performed for stationary and axis-symmetric flow conditions (no turbulence, no wind shear, no yaw misalignment, no tower influence, no tilt angle, and no cone angle).

Figure 1 defines some of the parameters that are used in the aerodynamic model.

Common situation (a≤0.38)

The basic equations of the blade element momentum theory are:

$$4a \cdot f(1 - a \cdot f) = \left(\frac{V_{eff}}{V_W}\right)^2 \cdot c_n \qquad 1$$

$$4a' \cdot f(1 - a \cdot f) = \sigma\left(\frac{V^2{}_{eff}}{V_w \cdot \Omega r}\right) \cdot c_t \qquad 2$$

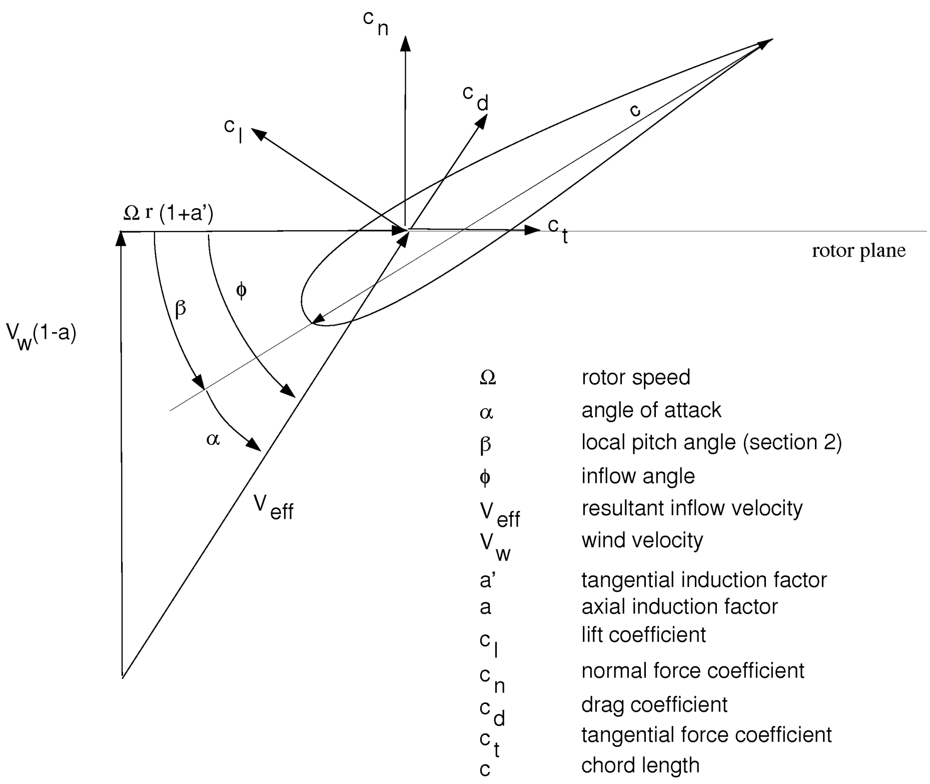

Figure 1: Definition of parameters

$$\tan(\varphi) = \left(\frac{1-a}{\lambda_r (1+a')} \right) \qquad 3$$

$$V_{eff} = \left(\frac{V_w (1-a)}{\sin(\varphi)} \right) = \left(\frac{\Omega \cdot r (1+a')}{\cos(\varphi)} \right) \qquad 4$$

In these equation σ is the solidity:

$$\sigma = \left(\frac{B \cdot c}{2\pi r} \right) \qquad 5$$

with B the number of blades.

λ_r is the local tip speed ratio:

$$\lambda_r = \left(\frac{\Omega \cdot r}{V_w} \right) \qquad 6$$

Note that c_n and c_t are known from the specified lift and drag coefficients as function of *a*. The Prandtl tip loss factor (*f*) is given by the next expression:

$$f = \left(\frac{2}{\pi} \right) \arccos \left[e^{-\pi \frac{R-r}{\Delta}} \right]$$

in which

$$\Delta = \left(\frac{2\pi r}{B} \right) \sin(\vartheta) \qquad 7$$

With these equations, it is possible to calculate the inflow angle φ from which the local aerodynamic forces on the blade elements can be derived. Summation of the aerodynamic forces over the blades yields the total blade loads (i.e. the aerodynamic power). Thereto the equations have been manipulated such that they become a function of the inflow angle (φ)

The equations 1 and 4 give:

$$4a \cdot f(1-a \cdot f) - \left(\frac{\sigma \cdot c_n (1+a)^2}{\sin^2(\varphi)} \right) = 0. \qquad 8$$

The equations 2 and 4 give:

$$4a' \cdot f\left(1-a \cdot f\right) - \left(\frac{\sigma \cdot c_t [1+a']^2 \lambda_r}{\cos^2(\varphi)} \right) = 0. \qquad 9$$

In the equations 8 and 9, λ_r and σ are known from the geometric and operational conditions. The tip correction factor and c_n and c_t are known as function of φ from equation 7 and the tables with profile coefficients respectively. Then the axial and tangential induction factors are also written as function of the inflow angle. From equations 1 and 2, it follows:

$$a'(\varphi) = \left(\frac{a(\varphi) \cdot c_t(\varphi)}{c_n(\varphi) \cdot \lambda_r} \right) \qquad 10$$

Note that substituting equation 10 in 9 yields equation 8. From the equations 3 and 10 it follows that:

$$a(\varphi) = \left(\frac{1-\lambda_r \cdot \tan(\varphi)}{1+\tan(\varphi) \cdot \dfrac{c_t(\varphi)}{c_n(\varphi)}} \right) \qquad 11$$

From the equations 8 to 11 the inflow angle φ can be solved numerically. This is described in section "*Solution Procedure*"

Turbulent wake situation (a>0.38)

For a > 0.38 a turbulent wake formula is assumed according to Wilson. Then equation 1 is replaced by:

$$0.96a \cdot f + 0.5776 = \sigma \left(\frac{V_{eff}}{V_w} \right)^2 \cdot c_n \qquad 12$$

This yields with equation 4

$$0.96a \cdot f + 0.5776 - \left(\frac{\sigma \cdot c_n (1+a)^2}{\sin^2(\varphi)} \right) = 0. \qquad 13$$

From the equations 12 and 2 it follows that:

$$0.96a \cdot f + 0.5776 = 4a' \cdot f \cdot \left(1-a \cdot f\right) \left[\frac{c_n}{c_t} \right] \cdot \lambda_r \qquad 14$$

Then equation 14 and equation 3 yield a quadratic equation from which the axial induction factor can be solved from the inflow angle φ:

$$a^2(4f^2) - af\left[4 + 0.96 \cdot \frac{c_t}{c_n} \tan(\varphi) + 4f\left(1-\lambda_r \tan(\varphi)\right) \right] \qquad 15$$

$$+ 4f\left[1-\lambda_r \tan(\varphi)\right] - 0.5776 \left(\frac{c_t}{c_n} \right) \tan(\varphi) = 0.$$

Solution procedure

Common situation ($a \leq 0.38$)

The unknown inflow angle φ is solved from equation 8, see below. The axial and tangential induction factors in these equations are known from the equations 11 and 10. The equations are solved numerically with regula-falsi in the following way:

1. First it is attempted to find the zero from equation 8.
2. It is assumed that the zero is between $\varphi = 0$ rad and $\varphi_{max} = \text{atan}(\lambda_r^{-1})$. Note that this approximately corresponds to a range of axial induction factor from a = 0 to a = 1.
   Thereto it is checked whether the zero is between $\varphi = 0$ and $\varphi_{max}/2$ or between $\varphi_{max}/2$ and φ_{max}. Evaluating the function values at these inflow angles performs this. Then the appropriate set of begin values for the regula-falsi procedure are known.
3. If equation 8 does not yield a solution between $\varphi = 0$ rad and $\varphi = \varphi_{max}$, than the search routine is given less strict constraints on inflow angle φ.
4. If equation 8 does not yield a zero dependend on the actual lamda the axial induction factor is set to 1, $\lambda \geq 50$, or to 0, $\lambda \leq 0.5$.

Turbulent wake situation (a>0.38)

In the turbulent wake situation, either equation 13 or equation 9 is solved. The axial and tangential induction factors are known from the equations 15 and 3.
The numerical procedure to find the inflow angle is similar to the procedure described above.

Rotor blade model

The rotor blade model is shown in figure 2. The blade is defined by chord, twist and thickness distributions. A distribution can be given by giving for at least 2 positions the chord or thickness. The twist distribution can be given by giving the twist at at least 1 position. The actual values of the chord, thickness and twist at the element boundaries are determined by linear inter/extra-polation of the given values. An aerodynamic profile has to be supplied at least for one radial station. The blade model assumes that the first indicated chord is the radius where the aerodynamic properties begin. The elements more to the rotor centre are assumed not to have aerodynamic properties. The following definitions are used in the aerodynamic model.

1. The first element with aerodynamic properties is the element containing the first radial station with a chord definition;
2. All interpolations between supplied values for chord, twist and thickness are linearly;
3. The tip twist angle is 0^o.

The radial stations to define a blade have to be selected carefully in conjunction with the number of elements. When e.g. the radial station of the largest chord is in the middle of an element the interpolation to the element boundaries can result in an element with a much smaller surface than expected at forehand. See e.g. in figure 2, where the dotted line indicates the actual used surface while the solid line indicates

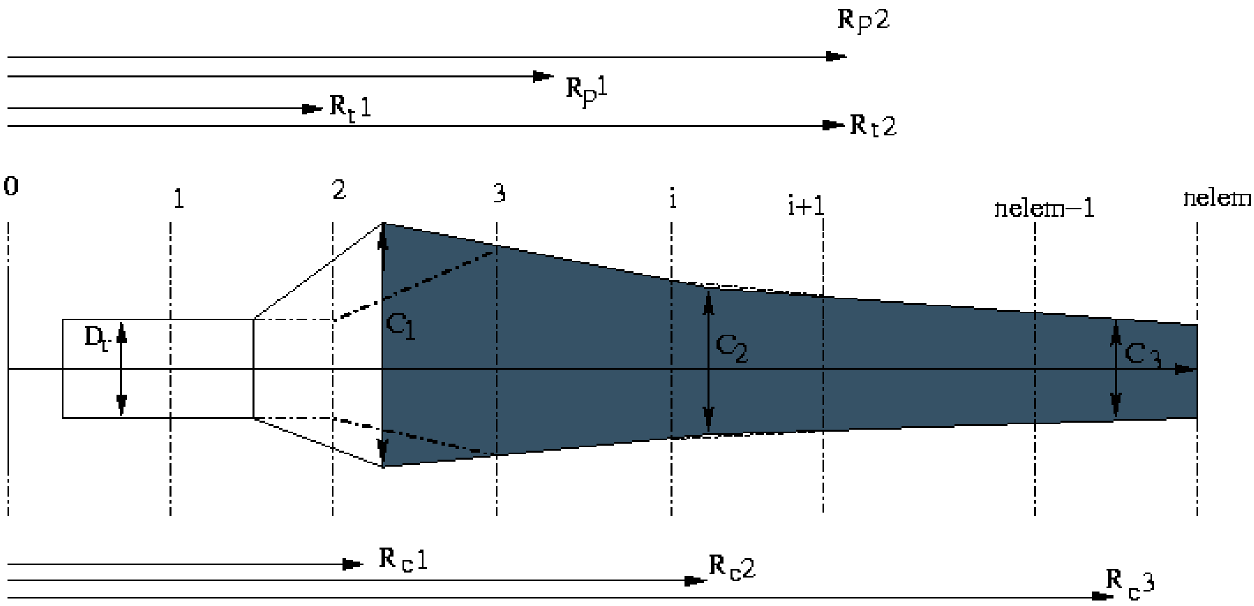

Fig. 2 the aerodynamic blade model

the desired chord distribution. Choosing the number of elements in such a way that the largest chord is just to the left of an element boundary can solve this.

Loading on the rotor blade

The above results in an axial and tangential induction factor which can be used to determine

- the inflow angle and
- the effective tip speed ratio

for the element. Then the effective inflow angle α and the effective wind speed can be determined. Together with the profile coefficients, cl and cd, the load on the blade element can be deduced according to the following equations.

$$\alpha = \varphi - \theta$$

This α leads to a c_l, and c_d in the profile coefficient database.

The effective wind speed for the element is

$$V_{eff} = V_{wind} * \lambda_{eff} * (1 + a') / \cos(\varphi)$$

The dynamic pressure is then equal to

$$P_{dyn} = \frac{1}{2} \rho V_{eff}^2$$

This results in the following blade element forces

$$df_{ax} = (c_l \cos(\varphi) + c_d \sin(\varphi)) * P_{dyn} * Chord$$

$$df_{\tan} = (c_l \sin(\varphi) - c_d \cos(\varphi)) * P_{dyn} * Chord$$

$$df_{torq} = df_{\tan} * r_i$$

Eventually, integrating over the rotor blade span, the element loads will result to the blade root and rotor centre loads and rotor performance.

Energy Yield Model

The energy yield is determined using the calculated power curve and the user defined Weibull distribution. The probability of occurrence of a certain wind speed interval, identified by V_{low} and V_{high}, is

$$P_i = EXP\left\{-\left(\frac{V_{low}}{a_H}\right)^{k_H}\right\} - EXP\left\{-\left(\frac{V_{high}}{a_H}\right)^{k_H}\right\}$$

The user defined Weibull distribution is given a reference height of 10 m, by the average wind speed, $\overline{U}_{10}$ and the shape factor k_{10}. These two parameters are extrapolated to the hub height according to the following equations, copied and derived from data in [9].

The wind shear profile is implemented using the standard logarithmic profile

$$\overline{U}_{hub} = \overline{U}_{10m} * \left(\frac{\ln\frac{H_{hub}}{z_0}}{\ln\frac{10}{z_0}}\right)$$

in which the Z_0 stands for the terrain roughness that needs to be supplied by the user.

The weibull scale factor is

$$a_H = 1.13 * \overline{U}_{hub}$$

The Weibull shape factor is extrapolated according to data also taken from [9], shown in figure 3 below. The quadratic curve fit results in the following relation for the Weibull shape factor

$$k_H = k_{10} * \left(1 + 0.00607385 * \text{Hub} - 2.64567\text{E} - 05 * \text{Hub}^2\right)$$

The wind speed distribution is determined for the same wind speed vector as the power curve and summed between V_{in} and V_{out} of the wind turbine to determine the average power of the wind turbine. Multiplied with the number of hours per annum this yields the yearly electricity production.

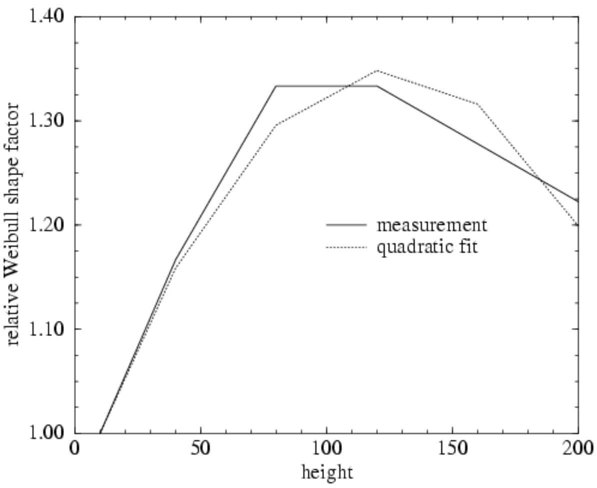

Figure 3 the height dependencies of the Weibull shape factor k

Load model (in Dutch)

Inleiding

Dit hoofdstuk beschrijft het blok 'BELAST', dat onderdeel uitmaakt van het blok 'KOSTPRIJS' van **S**tork **P**roduct **E**ngineering. Het doel van blok 'BELAST' is om het totale vermoeiingsspectrum te bepalen en deze tot een enkel getal, de vermoeiings-equivalente-belasting, te reduceren.
Eerst wordt het windvlagen model uit de doeken gedaan en daarna hoe de stap van een vlagenspectrum naar een belastingspectrum wordt gemaakt. Het windvlagen model is gebaseerd op het ***Nederlandse handboek Wind deel 3***. Een en ander is afhankelijk van turbine model, d.w.z. de turbine toeren/vermogens regeling.

Turbine regeling

Toeren regeling

Er zijn twee typen toeren regelingen gebruikt.

- constant toeren regeling waarbij toerental constant is als functie van de windsnelheid (iconst_speed = 1) $\Omega = \Omega_{rated}$
- variabel toeren regeling waarbij (iconst_speed <> 1)

$$\Omega = \lambda / R \text{ als } U < U_{rated}$$

$$\Omega = \Omega_{rated} \text{ als } U > U_{rated}$$

met	λ	snellopendheid
	Ω_{rated}	rated toerental
	U	windsnelheid
	R	rotorstraal

Vermogensregeling

Er zijn twee typen vermogensregelingen gebruikt:

- stall geregelde turbine waarbij de pitchhoek constant blijft en wordt ingegeven door de gebruiker,
- pitch geregelde turbine waarbij voor $U > U_{rated}$ het elektrisch vermogen constant wordt gehouden op P_{rated} door middel van het verstellen van de bladen. De pitchhoek die hiervoor moet zorgdragen moet

worden gevonden door de aërodynamische subroutine van ECN. De pitchhoek voor $U < U_{rated}$ wordt ingegeven door de gebruiker.

Windspectrum

Algemeen

De belastingen worden berekend met gebruikmaking van deterministische vlagen welke zijn gedefinieerd met 'Handboek ontwerpwindgegevens windturbines, versie 3'. Waar mogelijk zijn echter IEC gegevens als invoer gebruikt.
Een windvlaag wordt voorgesteld als een sinusvormige variatie met amplitude A rondom een 10 minuten gemiddelde windsnelheid U. De vaststelling van U en A en het aantal malen dat zo'n wisseling in de levensduur van de windturbine voorkomt wordt beschreven in het handboek.

Als invoer van het spectrum kan gebruik worden gemaakt van de IEC windklassen of door in de betreffende invoerschermen een Weibull vorm en gemiddelde op te geven.

Voor de 10 minuten gemiddelde windsnelheid op ashoogte (V_{ave}) heeft de IEC-norm een viertal klassen gedefinieerd:

Table 2 Basis parameters voor wind turbine klassen

Parameters		Wind turbine class			
		I	II	III	IV
Reference wind speed (V_{ref} (m/s))		50	42.5	37.5	30.
Annual average wind speed (V_{ave} (m/s))		10	8.5	7.5	6.
A	I_{15}	0.16	0.16	0.16	0.16
	a(-)	2	2	2	2
B	I_{15}	0.18	0.18	0.18	0.18
	a(-)	3	3	3	3

Het handboek stelt voor het bereik van 10 minuten gemiddelde windsnelheden te verdelen in klassen

Wind klasse	Windinterval	Rekenwaarde U
1	4-6	6
2	6-8	8
3	8-10	10
4	10-12	12
5	12-14	14
6	14-16	16
7	16-18	18
8	$18\text{-}V_{uit}$	V_{uit}

Table 3.De klasse indeling van de windsnelheden

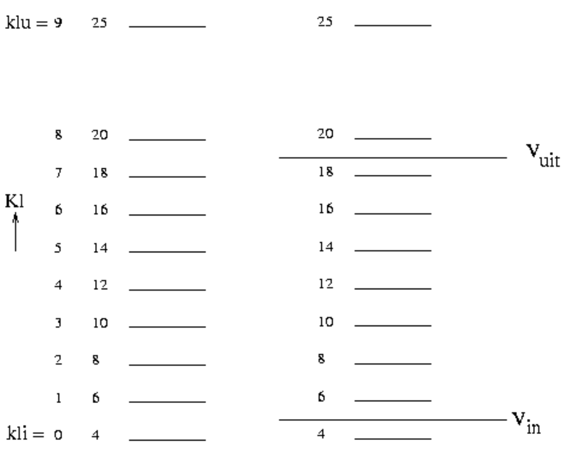

Figure 4 Inpassing Vin en Vuit windklasse

Het aantal windklassen dat wordt meegenomen is afhankelijk van de inschakelwindsnelheid V_{in} en de uitschakelwindsnelheid V_{uit}. Figuur 1 laat zien hoe dat gebeurt. Als voorbeeld is V_{in} = 6 m/s en V_{uit} = 20 m/s gekozen.

De windklassen die uiteraard worden meegenomen zijn díe klassen die tussen V_{in} en V_{uit} liggen. Er wordt geen windklasse gedefinieerd voor V_{in}. De kans van voorkomen van de windklasse direct boven V_{in} wordt bepaald uit de kans dat de 10 minuten gemiddelde wind ligt tussen V_{in} en 7 m/s. Er wordt tevens een windklasse met V_{uit} gedefinieerd.
De kans van voorkomen P_{kl} van een windklasse kl wordt bepaald volgens de Rayleigh verdeling, zie IEC 1400-1

$$P_{kl} = e^{-\left(\frac{U_{kl-1}}{a_H}\right)^{k_H}} - e^{-\left(\frac{U_{kl}}{a_H}\right)^{k_H}}$$

waarin U_{kl} de windklasse-snelheid is van klasse kl.

Turbulentie doorsnijding

In deze sectie worden vlagen gedefinieerd die niet het hele rotorvlak treffen. Dit fenomeen wordt turbulentiedoorsnijding genoemd. Deze plaatselijk in het rotorvlak optredende vlagen zijn klein qua amplitude en worden door de bladen gevoeld als een blad het rotorvlak doorloopt en hebben dus een frequentie van voorkomen die samenhangt met rotortoerental.

De turbulentie intensiteit wordt berekend met (IEC 1400-1, tweede editie):

$$\frac{\sigma_u}{U} = 1.2 \cdot I_{ave}\left(0.75 + 0.16 \cdot \frac{V_{ave}}{U}\right)$$

waarin

σ_u	standaard deviatie
U	windklasse snelheid

Voor het berekenen van de vlaagamplitude ten gevolge van turbulentie doorsnijding dient de longitudinale lengte schaal X_{Lu} (HB3) te worden bepaald uit de ashoogte H:

$$X_{Lu} = 82.3\,H^{0.2}$$

Een maat voor de verhouding tussen de energie in de nP-mode en de 0P-mode wordt gegeven door (HB3):

$$\frac{\sigma_n}{\sigma_u} = \frac{0.35}{n^{0.8}\,e^{-0.04\;n^{0.4}\;\frac{X_{Lu}}{D}}}$$

met	n	nummer van de mode (n = 1, 2, 3, 4)
	D	rotordiameter (D = 2 R)
	R	rotorstraal
	σ_n/σ_u	een maat voor de verhouding tussen de energie in de nP-mode en de energie in de 0P-mode.

De amplitude van de turbulentie doorsnijding voor een windklasse met windklasse snelheid U wordt uiteindelijk berekend met (HB3):

$$A_{nPt} = 2.15 \frac{\sigma_u}{U} \frac{\sigma_n}{\sigma_u} U$$

Het aantal malen voorkomen per uur n_{np} van een mode n volgt uit

$$n_{np} = \frac{n \ \Omega \ 3600}{2 \ \pi}$$

waarin Ω= rotortoerental in rad/s

Voor het aantal malen van voorkomen per levensduur n_{vj} geldt:

$n_{vj} = n_{np}\ 8760\ P_{kl}\ t_j$

waarin t_j de levensduur van de turbine is.

Bij de bepaling van de amplitude van de turbulentie doorsnijding van een bepaalde mode wordt de hogere mode erbij geteld

Dus

$A^*_{4pt} = A_{4Pt}$

$A^*_{3pt} = A_{3Pt} + A_{4Pt}$

$A^*_{2pt} = A_{2Pt} + A_{3Pt} + A_{4Pt}$

($A^*_{1pt} = A_{1Pt} + A_{2Pt} + A_{3Pt} + A_{4Pt}$)

De amplituden A^*_{4pt}, A^*_{3pt} en A^*_{2pt} worden gebruikt bij de belastingsberekening en worden berekend voor elke windklasse. Bij de A^*_{1pt} moet nog een deterministische term, de verticale windschering, bijgeteld worden.

Verticale windschering

De vlaagamplitude ten gevolge van verticale windschering wordt bepaald met behulp van een formule, welke een mix is tussen de IEC-norm en het Handboek

$$A_g = \{(z_2/H)^{\alpha} - (z_1/H)^{\alpha}\}\ U/2$$

met
$\alpha = 0.2$
$z_1 = H - 3/8\ 2\ R$
$z_2 = H + 3/8\ 2\ R$

De amplitude van de 1P windfluctuaties wordt daarmee

$A_{1pv} = A_g + A_c + A^*_{1pt}$

Waarin een correctieterm $A_c = 0.3 * \ln(z_2/z_1)$ is toegevoegd voor $z_2 > 25$ m.
De aldus berekende 1P-amplitude wordt meegenomen in het windspectrum.

Coherente vlagen

Coherente vlagen zijn windvlagen die het gehele rotorvlak treffen.

Vlaagduurklasse

Binnen zo'n windklasse worden ook de tijdsduur (vlaagduurklasse) en de amplituden in klassen verdeeld.

Table 4 De klasse indeling van de vlaagduurklasse

Vlaagduur klasse vk(-)	Interval T(s)	Rekenwaarde T_A(s)	Rekenwaarde T_d(s)	Aatal/uur N_{vk}(-)
1R	2 - 30	30	7.5	240

met T_A rekenwaarde vlaagduurklasse voor berekening van de vlaagamplitude
en T_d rekenwaarde vlaagduurklasse voor berekening van het aantal vlagen per uur.

Amplitude

De grootte van de amplitude van een coherente vlaag in een windklasse is verdeeld in drie groepen die worden gekarakteriseerd door de kans P_A dat de amplitude wordt overschreden. Hiermee is ook vastgelegd hoe vaak een dergelijke vlaag voorkomt. Tabel 5 geeft de relatie tussen kans van voorkomen en overschrijdingskans.

Table 5 De verdeling van de vlaagamplituden naar overschrijdingskans

Overschrijdingskans P_A(%)	C_A(-)	kans van voorkomen P^*(%)
10	1.00	80
1	1.64	18
0.01	2.52	2

De amplitude van de coherente vlagen (0P) is afhankelijk van de windklasse. Voor het berekenen van de vlaagamplitude van de coherente vlagen is nodig

$$\frac{\sigma_{u,eff}}{U} = \frac{\sigma_u}{U} \left[1 - c_{vk}\, D \left(\frac{\sigma_u}{U} - 0.5 \left(\frac{\sigma_u}{U}\right)^2\right)\right]$$

waarin c_{vk} constante
$s_{u,eff}$ effectieve turbulentie intensiteit

De drie amplituden van de 0P-mode kunnen met behulp van tabel 4 worden berekend uit:

$$A_{0P\,C_A} = 0.052\, C_A\, H^{-0.19} \left(1 + 5.6 \frac{\sigma_{u,eff}}{U}\right) \left(T_A\right)^{1/2} \left(1 + 0.34\, U^{1/3}\right) U$$

waarbij C_A = 1.00, 1.64 of 2.52.

De amplitude van de 0P-mode waarmee de belastingen moeten worden berekend wordt mede samengesteld uit de hogere modes volgens

$A^{*}_{0P\,CA} = A_{0P} + A_{1Pv} + A_{2Pt} + A_{3Pt} + A_{4Pt}$

Het aantal wisselingen per levensduur bedraagt

$n_{vj\,CA} = t_j\ 8760\ N_{hr}\ P^{*}/100\ P_{kl}$

met P^{*} 80, 18, 2
N_{hr} 3600/(2 T_d) = aantal wisselingen per uur
t_d rekenwaarde vlaagduur ter bepaling van een aantal vlagen per uur

Resultaat

Het resultaat van een windspectrum berekening is een aantal van i_max_wind (= aantal windklassen * 7) data regels waarin per regel is opgenomen

- de windklasse snelheid (U_i)
- de amplitude (A_i)
- aantal wisselingen van de vlaag per levensduur ($sn_i = n_{vj}$)
- P-mode (mode).

Per windklasse bestaat het spectrum dus uit 7 vlagen bestaande uit:

Table 6 Vlagen per windklasse

Omschrijving	U_i	A_i	sn_i	mode
turbulentie doorsnijding	U	A^{*}_{4Pt}	n_{vj4}	4
turbulentie doorsnijding	U	A^{*}_{3Pt}	n_{vj3}	3
turbulentie doorsnijding	U	A^{*}_{2Pt}	n_{vj2}	2
turbulentie doorsnijding wind schering	U	A_{1pv}	n_{vj1}	1
coherente vlaag	U	$A^{*}_{0P\,(CA=1.00}$	$n_{vj\,CA=1.00}$	0
coherente vlaag	U	$A^{*}_{0P\,(CA=1.64}$	$n_{vj\,CA=1.64}$	0
coherente vlaag	U	$A^{*}_{0P\,(CA=2.52}$	$n_{vj\,CA=2.52}$	0

Beperkte set vlagen

Tabel 6 geeft een overzicht van een beperkte set vlagen die kunnen worden gebruikt om snel een spectrum voor een stall geregelde turbine en een pitch geregelde turbine te berekenen.

Table 7 Vlaaggegevens van beperkte set

mode	stall		pitch		aantal wisselingen
	U	A	U	A	n_vj
0P (18%)	0.9 V_{rated}	0.85 U	V_{uit}	0.85 U	t_j*8760 3600/(2 t_d) 0.04 0.20
0P(100%)	0.9 V_{rated}	0.65 U	0.67 V_{rated}	0.65 U	t_j*8760 3600/(2 t_d) 1.00 0.80
1P	0.9 V_{rated}	0.33 U	0.67 V_{rated}	0.33 U	t_j*8760 3600 $\Omega/(2\ \pi)$
4P	0.9 V_{rated}	0.03 U	0.67 V_{rated}	0.03 U	t_j*8760 3600 $\Omega/(2\ \pi)$

Belastingsspectrum

Introductie

Voor de bepaling van de kosten van de turbine zijn onder andere vermoeiingsbelastingen op enkele componenten nodig. Deze moeten worden aangeleverd als equivalente belastingen welke worden verkregen uit de vermoeiingsspectra van de axiaalkracht op het blad op r = 0 m (Fx r=0) en de klapmomenten My op de bladsneden. De spectra worden berekend met behulp van een of twee belastingcurve(s). Een belasting curve is de relatie van de belasting als functie van de windsnelheid.
Om de berekening van equivalente belastingen te illustreren wordt uitgegaan van een turbine met variabel toeren en pitch regeling versus een constant toeren overtrek regeling. Voor het gemak wordt als belasting het klapmoment op r=0 beschouwd. Voor de overige doorsneden kunnen de krachten en momenten op een zelfde werkwijze worden verkregen.

Belastingscurve

Bij de berekening van de belasting t.g.v. een windvlaag worden per windvlaag een of twee belastingscurves berekend.

1. één voor een ideale regeling (equi). Deze curve hoeft slechts eenmaal te worden berekend.
2. één voor een slechte regeling (non). Deze curve moet voor elke windklasse opnieuw worden berekend.

Met de beschikbaarheid van het rotortoerental Ω en de pitchhoek θ als functie van de windsnelheid U kan de aerodynamische subroutine, de bijbehorende belastingen zoals Fx(r=0), de klapmomenten op de bladsneden en het vermogen berekenen. Uiteraard zijn geometrie gegevens beschikbaar zoals koorde en twist die ook nodig moeten zijn voor het bepalen van de P-V-curve. Een belastingscurve moet worden berekend van V = 1 tot $V = 2(V_{uit} + 1)$ m/s.

Ideale pitch regeling

Voor de berekening van de belastingswisseling ($\Delta M_{y\ r=0\ i}$) en het gemiddelde niveau ($M_{y\ r=0\ ave\ i}$) ten gevolge van een vlaag wordt uitgegaan van een belastingscurve. Hieronder wordt verstaan M_y (r=0) als functie van de windsnelheid V. Voor een ideale pitchregeling geldt een curve zoals gegeven in figuur 2. Tevens is aangegeven hoe het vermogen P, pitchhoek θ en het toerental W verandert als functie van de wind V. De curve voor een ideale pitch regeling wordt verkregen door de aerodynamische subroutine aan te bieden:

- wind U
- rotortoerental als functie van U
- een pitchhoek θ voor $U < U_{rated}$

en

– een pitchhoek θ voor $U > U_{rated}$ (voor stall geregelde turbines)
– rated vermogen voor $U > U_{rated}$ (voor pitch geregelde turbines).

In dit laatste geval zal de 'aërodynamische routine' zelf een pitchhoek moeten zoeken.

De belastingswisseling wordt bepaald zoals aangegeven in figuur 2. De wisseling wordt bepaald door de belastingen voor $V_{min\ i} = U_i - A_i$ m/s en $V_{max\ i} = U_i + A_i$ m/s te bepalen. Eventueel minima en maxima tussen $V_{min\ i}$ en $V_{max\ i}$ worden verwerkt. De range is dan:

$$\Delta M_{y\ equi\ i} = (M_{y\ max\ equi\ i} - M_{y\ min\ equi\ i})*factor.$$

$$M_{y\ ave\ equi\ i} = (M_{y\ max\ equi\ i} + M_{y\ min\ equi\ i})*factor/2.$$

Eventueel kan een belastingsfactor worden toegevoegd.

Trage pitch regeling

Bij een trage pitch regeling geldt niet meer de stationaire curve waarbij de pitch hoek en het toerental verandert met de variatie van de wind tijdens een vlaag. Pitchhoek en toerental zijn niet in evenwicht met de windsnelheid (non-equilibrium). De belastingscurve die dan geldt is er een waarbij de pitchhoek en het toerental constant blijft. Díe pitchhoek en toerental worden gekozen die passen bij de 10 minuten gemiddelde windsnelheid U van de betreffende windklasse. Daartoe moet aan de aërodynamische routine de windklasse snelheid met het bijbehorende rotor toerental worden aangeboden. De routine zal dan een pitchhoek dienen te vinden om, indien nodig, het vermogen te beperken op P_{rated}. Met de gevonden pitch hoek en het rotortoerental dient een belastingscurve te worden berekend waarbij de pitchhoek en het rotortoerental constant worden gehouden.

In figuur 3 is de belastingscurve van een trage regeling gegeven naast die van de ideale stationaire curve. De belastingswisseling van een dergelijk trage regelaar is getekend in figuur 3. Eventueel kan een belastingsfactor worden toegevoegd.

$$\Delta M_{y\ non\ i} = (M_{y\ max\ non\ i} - M_{y\ min\ non\ i})\text{*factor.}$$

$$M_{y\ ave\ non\ i} = (M_{y\ max\ non\ i} - M_{y\ min\ non\ i})\text{*factor/2}$$

Realistische pitch regeling

In werkelijkheid zal een regeling niet ideaal zijn maar ook niet oneindig traag. De traagheid kan met behulp van een tijdconstante τ_{reg} van de regeling worden ingevoerd.

De mate waarin de regeling een fluctuatie kan volgen wordt bepaald met:

$$eve = \exp(-\tau_{reg}/(2T_d)) \quad \text{voor 0P vlagen en}$$

$$eve = \exp(-\tau_{reg}/(T_{mode\ n})) \quad \text{voor hogere modes}$$

waarin T_d = vlaagperiode tijd (halve sinus)
$T_{mode\ n} = 2\ \pi/(n\ \Omega)$

met n mode (1, 2, 3, 4)
Ω toerental

$$\Delta M_{y\ i} = eve * \Delta M_{y\ equi\ i} + (1-eve) * \Delta M_{y\ non\ i}$$

$$M_{y\ ave\ i} = eve * M_{y\ ave\ equi\ i} + (1-eve) * M_{y\ ave\ non\ i}$$

Voor een stall geregelde constant toeren turbine zal de evenwichtscurve gelijk zijn aan de niet-evenwichtscurve.

Resultaat

Het resultaat van deze exercitie is een aantal van 'i_max_wind' regels met:

- belastingsrange ds_i (=$\Delta M_{y\ i}$)
- level ls_i (= $M_{y\ ave\ i}$)
- aantal wisselingen sn_i

Een dergelijk blok met belastingen moet worden aangemaakt voor Fx(r=0) en de klapmomenten voor de bladsnedes.

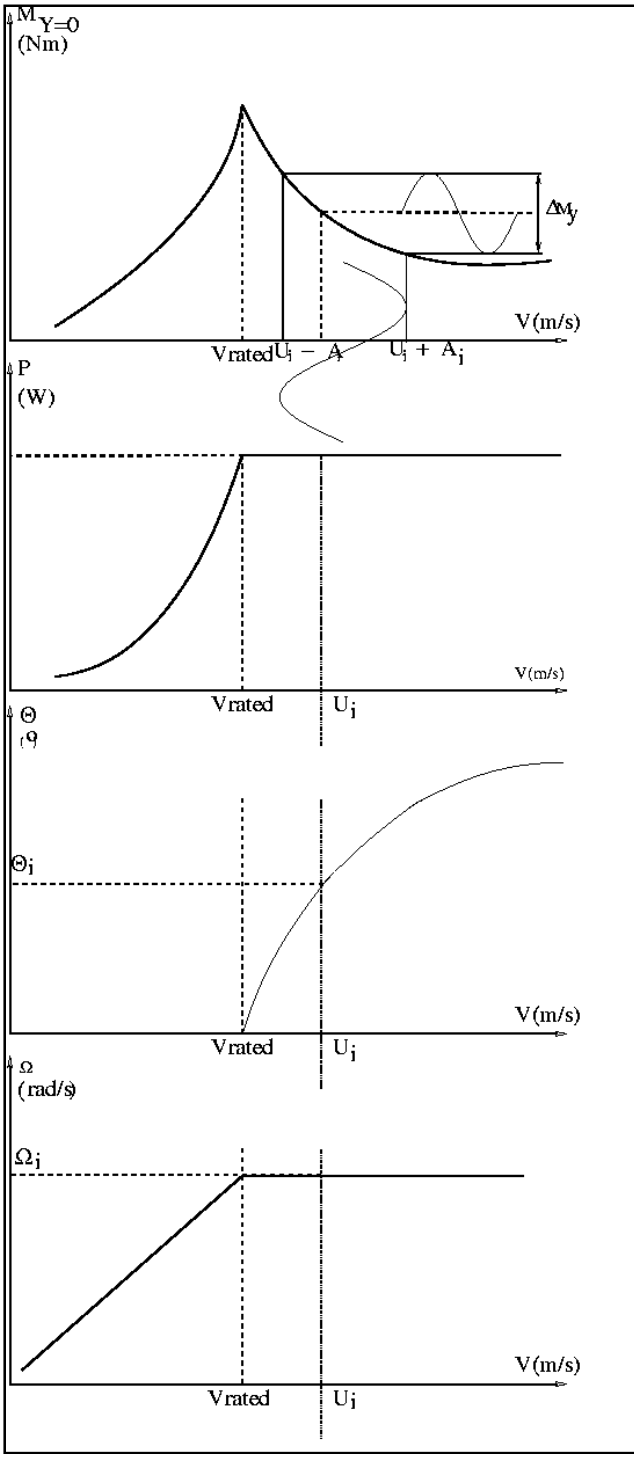

Figure 5 de evenwichtskrommen

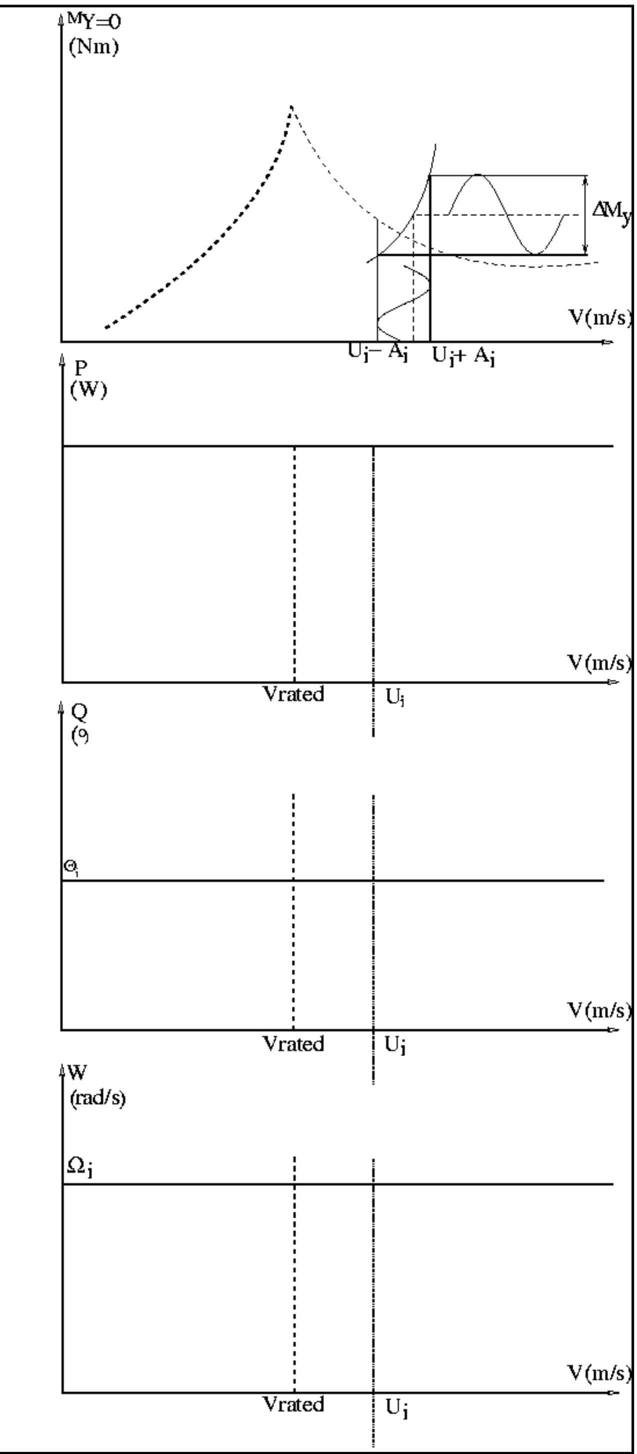

Figure 6 de niet evenwichtskrommen

Vermoeiing equivalente belasting

Inleiding

De hiervoor berekende belastingsspectra zijn te complex om snel een windturbine mee te ontwerpen. Echter door gebruik te maken van de vermoeiing equivalente belasting kan eenvoudig en snel bepaald worden of vermoeiing danwel statische sterkte ontwerp sturend is. Hierna wordt aangegeven hoe de vermoeiing equivalente belasting cycle kan worden berekend uit het variabele amplitude belastingsspectrum.

Schade

Voor de bepaling van de vermoeiingschade is van belang:

- ranges ds_i,
- levels ls_i en
- aantal wisselingen sn_i
- de s-n-lijn van het gebruikte materiaal.

De berekening van de schade pm_i van een belasting t.g.v. een $windvlaag_i$ is weergegeven in figuur 4. Het effect van het level van de belasting ls_i is voor de eenvoud niet meegenomen. De schade pm_i van een belasting i (ds_i) is het quotiënt van het aantal wisselingen van belasting I(sn_I) en het aantal toegestane wisselingen gn_i bij de range ds_i volgens de s-n lijn behorende bij het gebruikte materiaal.

$$pm_i = sn_i/gn_i$$

Indien het level van belang is, is gn_i ook een functie van het level.
Vervolgens dient de schade pm_i van alle belastingsgevallen te worden gesommeerd volgens de Pålmgren-Miner regel tot een totale schade pmsom (alle windvlagen (i_max_wind)).

$$\textit{Vermoeiingsschade} = \sum_{i=1}^{imaxwind} pm_i$$

Afhankelijk van het materiaal kan ook het niveau van belang zijn voor de schadeberekening. Een voorbeeld van een dergelijk materiaal is vezel versterkt kunststof.

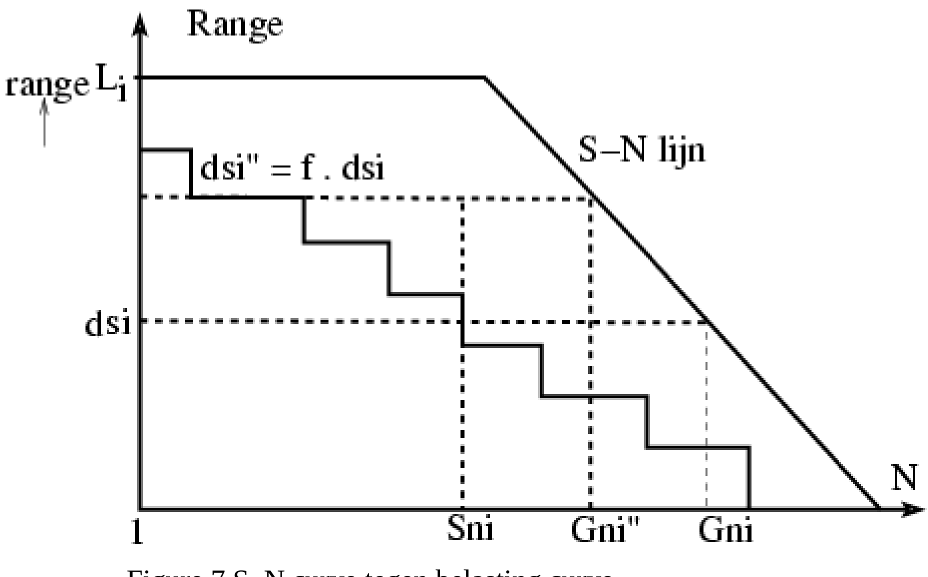

Figure 7 S_N curve tegen belasting curve

Equivalente belasting

De totale vermoeiingsschade zal groter worden als de ranges ds_i met een factor f≥1worden verhoogd. Het aantal wisselingen sn_i verandert weliswaar niet, maar de toegestane wisselingen gn_i zal bij een belasting f * ds_i lager zijn waardoor $pm_i = sn_i/gn_i$ groter zal zijn. In figuur 4 is te zien wat het effect is voor bijvoorbeeld het verhogen van range ds_i tot ds^*_I = f * ds_i op de verhouding tussen de sn_i en gn_i. Er kan een factor f worden bepaald waarvoor geldt dat de totale schade pmsom = 1.
De equivalente belasting is een belasting die eenmaal voorkomt en die dezelfde schade zal geven als het gehele spectrum en is daardoor een maat is voor het gehele spectrum.
De equivalente belasting is de belasting die wordt verkregen door de waarde van de s-n-lijn bij n=1 (L,) te delen door factor f waarvoor de totale schade=1 ontstaat.

Toepassing in BLADOPT

De belasting kan ook equivalent worden gemaakt voor een ander aantal. Voor staal is het gebruikelijk om de belasting equivalent voor $n=10^7$ te gebruiken, zodat de constructie kan worden beoordeeld met bijvoorbeeld de kerfwaarde van een lastype volgens de Eurocode.

Bij staal heeft de S-N kromme meer details. Zo mag de vloeigrens niet worden overschreden. Omdat dit voor de meeste staalsoorten optreedt bij $n=10^5$, worden in Bladopt alle ranges f*ds_i met een aantal $ns_i < 10^5$ geschaald naar $ns_i = 10^5$. Volgens deze procedure loopt de S-N lijn voor $n<10^5$ vlak en wordt de vloeigrens niet overschreden.
Voor staal is er ook sprake van een vermoeiingsgrens, waarbij boven $n>10^7$ de toelaatbare spanning niet meer afneemt. In Bladopt wordt deze eigenschap gemodelleerd door ranges met $sn_i>10^7$ te schalen naar $sn_i=10^7$. Volgens deze procedure loopt de s-n lijn voor $n > 10^7$ eveneens vlak. Als richtingscoëfficiënt van de S-N kromme voor staal wordt m = 3 gebruikt. De knik van m = 3 naar m = 5, welke volgens de Eurocode moet worden toegepast als de vloeigrens is overschreden, wordt voorlopig niet gebruikt. In feite wordt door bovengenoemde procedure de vloeigrens niet overschreden.

Voor vezelversterktekunstoffen wordt het aantal omwentelingen van de rotor gedurende de levensduur van de turbine als equivalent aantal gebruikt.
De ingevoerde UTS waarde, welke een waarde is voor de sterkte van het GVK wordt door Bladopt omgerekend naar de vermoeiingsspanning, welke volgens de S-N kromme hoort bij het totaal aantal omwentelingen van de turbine (1P). Vervolgens zal de bladconstructie worden beoordeeld met de 1P-equivalente belastingen.
Voor GVK wordt een richtingscoëfficiënt van m=10 gebruikt. De gemiddelde spanning wordt in Bladopt conservatief niet in rekening gebracht.

Method of Fatigue Equivalent Loads (FEL)

The fatigue equivalent load can be used to make preliminary designs as long as the limitations of the method are known. The fatigue equivalent load can be a measure of the fatigue load spectrum knowing the load and the number of cycles. The following assumptions are made formulating the fatigue equivalent load:

- fatigue damage formulation or summation of Pålmgeren-Miner is valid;
- a simple fatigue formulation, like a straight line on a log (N) – log (σ_r) graph
- load – stress relation is linear;
- a constant amplitude load cycle occurring $N_{eq.}$ times induces an equal amount fatigue damage as the “true” variable amplitude design load spectrum.

In the fatigue formulations the factor U.T.S. represents the allowable tensile or compressive strength. The Miner sum can be calculated from this U.T.S. value, the stress spectrum and the fatigue formulation.
An inverse method would use the spectrum, Miner-sum and fatigue formulation to calculate a wanted value for U.T.S. This inverse method is used to calculate the FEL: a static load representing the total load spectrum for a given formulation and Miner sum. With this method the actual extremes of the load and the FEL's are derived from the spectrum.

If the spectrum comprises of both positive and negative load values two FEL values are calculated.

The FEL is calculated as follows. For every relevant combination of mean stress and amplitude in the spectrum a quasi U.T.S. (Uts') is calculated. With the maximum of all Uts' values as starting value for UTS - guess the Miner summation for the spectrum is calculated, in general this sum will be too large. From the initial value of UTS-guess and the sum a second value for UTS_{guess} is found. Starting from this second value and using a root finder routine like the cord-method the FEL is calculated.

Having calculated the necessary loads a structure can be designed from the combined loads. The stress reserve factor (SRF) is found easily but the lifetime reserve factor (LRF) can not be calculated directly. An approximation for the LRF is found as follows. For the critical load (often the flapping moment) the Miner sum is calculated using a U.T.S. equal to the FEL divided by SRF. The LRF is defined as this Miner sum divided by the target value.

Cost functions

Introduction

Two types of cost functions are implemented in **BLADOPT:**
- engineering and
- parametric cost functions.

The engineering cost functions are actually only real engineering models for the tower and rotor blade while for the remaining components parametric functions, using geometric and or response parameters of the **belast** module as input.
The parametric cost functions are based on geometric properties and expected number of products made in the series production.

The user can alter the cost modules in two ways. First the cost coefficients can be updated. The cost coefficients are in two, ASCII, files called, **defins.def**, for the engineering cost functions and **define.def** for the parametric cost functions. Secondly the source code can be changed and recompiled and linked into the model.dll. The second method can only be done when a Fortran compiler, is available and only when the proposed changes do not affect the rest of the program. In the annexes all the relevant include files are listed with the content of the COMMON blocks and a very short description of the variables.

Engineering Cost Functions

There are cost functions for all major components and systems cost items, like assembly and wind farm infrastructure cost. The major components are:
- Safety and control,
- Hub,
- Drive train,
- Electrical system,
- Nacelle,
- Yaw mechanism,
- Tower,
- Blades.

In the following for each cost item the model is described.

The nomenclature used in the cost functions is:

P_{rated}	Rated Power	kW
Dia	Rotor diameter	m
price	Cost of component currency depends on the values of constants	
c_c_i	Price *coefficient*	

H	Tower height	m
sf(_i)	Service factor	-
#_blades	Number of blades	-
lvarsp	Logical (0/1) indicating. **.TRUE.** when variable speed power train	-
#_gen	number of generators	-
a,b,c	cost coefficients	

In the formulas some parameters are **design** parameters, some are (default) *input* parameters and some are ***response*** parameters. The design parameters, which are not supplied via the user interface, are read from the file ***define.def*** that should be in the same directory as the project file.

Wind farm

The cost of the wind farm, e.g. the connection to the grid, the cost of the infrastructure and the cost of the developer are strongly related to the rated power of the wind turbine.

$$\text{Price} = c\_c\_1 * \mathbf{P_{rated}} + c\_c\_2 * \mathbf{Dia} + c\_c\_3$$

Assembly

The assembly cost are all cost made between the factory and when the turbine is completely installed, e.g. transport cost, crane cost other handling cost.
The cost of assembling is strongly related to the rotor diameter and the tower height.

$$\text{Price} = c\_c\_1 * (\mathbf{Dia}/30.)^2 * (\mathbf{H}/42.)^{0.5} * sf$$

The default values for *c_c_1* = 30.000,
and *sf* = 1.005
that can be changed in the file ***defines.def***.

Safety and Control

The safety and control cost are the price of the control and safety systems. The cost is not very sensitive to the design parameters of the wind turbine. However a passive stall regulated wind turbine is of course cheaper than an active pitch regulated wind turbine.

$$\text{Price} = c\_c\_1 + c\_c\_2 * sf\_1$$

If active control

$$\text{Price} = \text{price} + c\_c\_3 * sf\_2$$

In which the values for c_c_1 = 8.000,
c_c_2 = 10.000,
c_c_3 = 3.000,
and for sf_1 = 1.2
sf_2 = 2.0

that can be changed in the file ***defines.def***.

Hub

The hub structure is between rotor blade flange and rotor shaft. The cost of the hub is strongly related to the rotor dimensions, i.e. rotor diameter.

$$\text{Price} = c\_c\_1 * (\mathbf{Dia}/25.)^{2.7} * c\_c\_2 * \mathbf{\#\_blades} + c\_c\_3$$

In which the values for c_c_1 = 8.000,

c_c_2 = 2.500,
c_c_3 = 1.250,

that can be changed in the file ***defines.def***.

Drive Train

The drive train is gearbox and gearbox support. The price is strongly related to the input torque of the gearbox, depending on the control strategy.

$$\text{Price} = c\_c\_1 * \mathbf{P}_{\mathbf{rated}} * (sf/1.8) * (1./\Omega)$$

The service factor *sf* is defined by the control strategy, sf is determined according to the following table

	variable speed	constant speed
passive power regulation		1.5
active power regulation	1.2	1.8

In which the values for c_c_1 = 900,
which can be changed in the file ***defines.def***.

Electrical System

The electrical system consists of the generator and the remaining electrical system not included in the wind farm cost. The cost of the electrical system is mainly driven by the rated power.

The cost of the generator is nearly linear with the rated power, with a weak quadratic part.

The cost of the electrical system is linearly with rated power. For variable speed systems an extra cost item should be added for power electronics and control electronics.

The cost is taken to be:

$$\text{Price} = p\_gen + p\_el + lvarsp * p\_var$$

In which

$$p\_gen = \#\_gen * (a * \{\mathbf{P}_{\mathbf{rated}}/\#\mathbf{\_gen}\}^2 + b * \{\mathbf{P}_{\mathbf{rated}}/\#\mathbf{\_gen}\} + c)$$

$$p\_el = c\_c\_2 * \mathbf{P}_{\mathbf{rated}}$$

$$p\_var = c\_c\_1 * [(\mathbf{P}_{\mathbf{rated}}/250.)^{0.2} + (\mathbf{P}_{\mathbf{rated}}/250)^{0.8}]$$

In which the values for c_c_1 = 48.E+03,
c_c_2 = 65,
and a = 0.25,
b = 25,
c = 50,
and ngen = 1

which can be changed in the file ***defines.def***.

Nacelle

The nacelle consists of the bedplate and housing. The main design driver is the rotor diameter. Therfore the bulk effect for larger dimensions will also be used so the cost will be proportional to the diameter to the power 2.7. The nacelle mass is needed to determine the tower eigen frequency. The mass will be determined using a mass coefficient. The price is determined using a cost coefficient of the nacelle.

$$Mass_{top} = m\_c\_1 * (\mathbf{Dia}/25.)^{2.7}$$

$$price = c\_c\_1 * Mass_{top}$$

The values for m_c_1 = 6.E+03,
and c_c_1 = 1.375,
that can be changed in the file ***defines.def***.

Yaw Mechanism

The yaw mechanism includes the yaw bearing, yaw drive and yaw controller. The dimensions are assumed to be proportional to the rotor dimensions.
The cost is assumed to be proportional with the rotor diameter to the power 2.7.

$$\text{Price} = c\_c\_1 * (\mathbf{Dia}/25.)^{2.7}$$

In which the values for c_c_1 = 6.5E+03,
that can be changed in the file ***defines.def***.

Tower

The tower cost is determined on the basis of the tower mass in a simple manner:

$$\text{Price} = c\_c\_1 * \text{Mass}_{tower}$$

The tower weight is determined with a tower design model, which is based on a relative simple engineering model. This means that the tower dimensions, tower radius and wall thickness distribution is determined in such a way that the mass of the tower is minimal with the following design restrictions:

three strength requirements:
1 extreme loads,
2 fatigue loads,
3 buckling.

The tower design varies the taper of the diameter and the wall thickness linearly with the height.
Assumptions in the design model are that:

- Dia_{top} = 1. + *c_Dia_top* * **Dia**,
- T_towerTop = 0.01 [m],
- diameter varies linearly with the height,
- wall thickness varies linearly with the height.

In Figure 8 the model of the tower is shown.

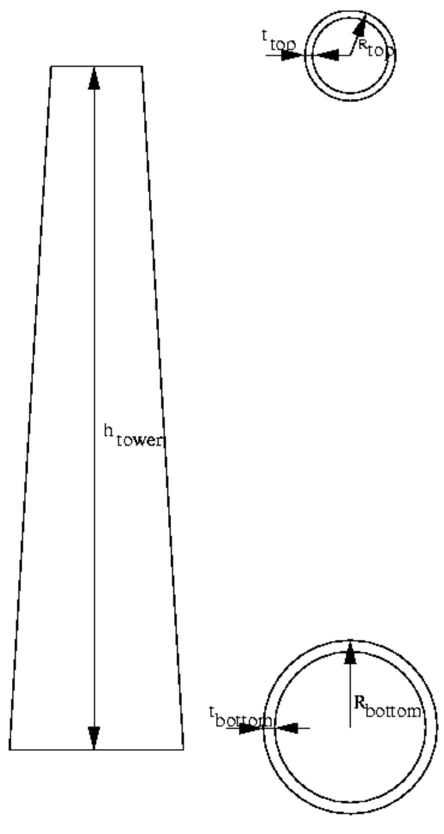

Figure 8 the tower model

Tower resonance requirements are shown in the table below:

soft-soft	ν_{tower}	<	$a \,.\, \Omega_{\mathbf{min}}$			
stiff-soft	ν_{tower}	>	$b \,.\, \Omega_{max}$	&	ν_{tower} <	a . **#_blades** Ω_{min}
stiff-stiff	ν_{tower}	>	*c* . **#_blades** . Ω_{max}			

The strength and eigenfrequency of the tower is determined with simple beam theory, including the nacelle and rotor mass for the first bending eigenfrequency.

The model results in a simple tower design described with the tower taper and the wall thickness taper which together with the tower height and the top diameter gives a complete description of the tower. The resulting design complies with the given constraint w.r.t. eigenfrequency and has sufficient strength w.r.t. the given material strength parameters.

The engineering model results in:

- $Mass_{tower}$
- ν_{tower}
- Tower foot diameter
- Tower footwall thickness.

Blades

The price of the blades is determined by the weight of the blade in a simple manner:

$$Price = c\_c\_1 * \#_{\mathbf{blades}} * Mass_{blade} - tip_{mass} + c\_c\_2 * tip_{mass}$$

The mass of a rotor blade is determined with a rotor blade design model, based on a simple engineering model

Blade definition

The blade is divided in three sections,

- flange;
- root;
- airfoil

see figure 2 for the blade geometry definitions.

The blade is defined by 4 different radius dependent quantities,

1. chord distribution
2. twist distribution
3. thickness distribution
4. profile distribution

The blade model uses the first radius where a chord is defined, $R_C(1)$, as the start of the first aerodynamic active section. This chord is also used to determine the diameter of the blade root, which has a fixed ratio with C_1. This ratio is given in the **defines.def** file.
The chord, thickness and twist are linearly inter- or extrapolated from the given input to the blade element boundaries. This implies that at least two radial positions are needed to define a chord and thickness distribution. For the twist only one radial position is sufficient because the twist is zero at the tip by default.
The airfoil sections start at the first radial position where a chord has been defined and run to the first radial position where a profile is defined. If, like in the figure above, no radial position at the tip is defined for the airfoil distribution, the last indicated airfoil would also be used for the tip section.
A tip angle can be enforced through the user interface, see tab general.
The root section is a cylindrical section with a diameter, that equals a fixed ratio of the maximum chord. This ratio, D_{root}/C_1 can be defined in the file **defins.def** but has a default value of 0.55.
The airfoil section is build up of a skin and combined with a double elliptical or box type beam, see example with a double elliptical cross section in figure 9.
The cross sections at the element boundaries are designed in such a way that they can resist the maximum static load and the equivalent fatigue load.

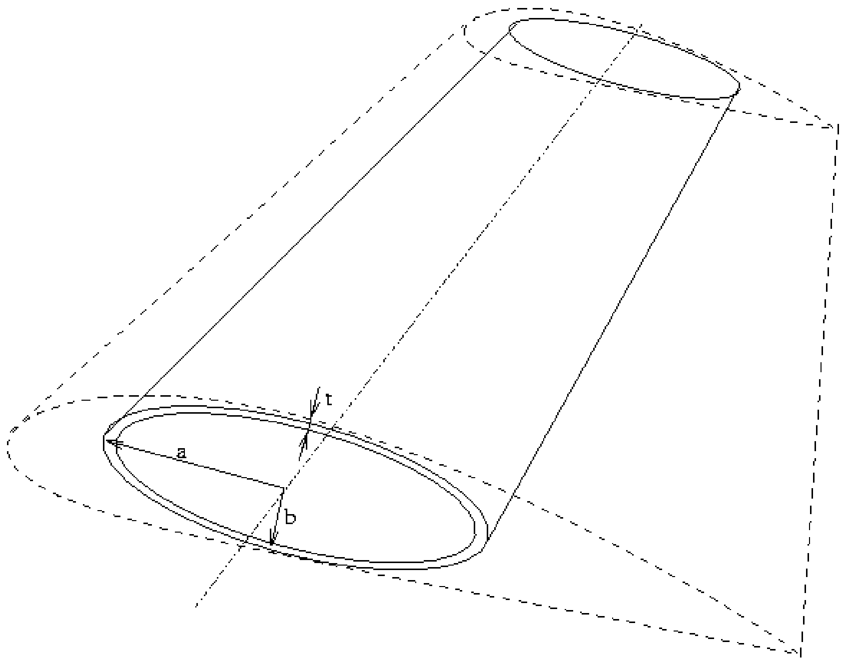

Fig. 9 Blade section with load carrying beam

For each section a minimisation is performed on the cross sectional area, constraint to be able to bear the fatigue and static loads. This results in the definition of two concentric ellipses or boxes. The outside ellipse or box is defined by the aerodynamic shape of the section, the inside ellipse or box by the resistance moments needed to carry the loads.
The properties, which are needed to design the blade, result from the load spectra analysis and from constants in the **defins.def** file, like material and price quantities.

The properties, which are defined in the defins.def file, are:

c_c_1	the cost per kilo blade mass	NFL/kg
c_c_2	the cost of a kilo tip mass	NFL/kg
c_mass	constant in tip mass equation; tipmass = c_mass $R^{2.7}_{tip}$	kg/m
sfcntr	safety and control factor	-
lbox	true for box type construction else elliptical	-
Espar	Elasticity modulus of the spar	[Pa]
rho spar	density of spar material	kg/m^3
rho skin	density of skin material	kg/m^3
σ_{max}fat	1 cycle allowable fatigue stress	[Pa]
m_{spar}	slope of the S-N curve	-
σ_{max}stat	max allowable max stress	[Pa]
t_{min}	minimum skin thickness	[m]
csoverca	chord for strength over chord for aerodynamic properties	

The σ_{max}fat is transformed into the n-cycle equivalent fatigue stress

$$\sigma_{fat.}eq = \left((\sigma_{\max} fat.)^{m_{spar}} \Big/ \#_{rotations} \right)^{1/m_{spar}}$$

in which $\#_{rotations}$ stands for the total number of rotor rotations or 1 P cycles, which is determined in the spectrum module.

DEFINS.DEF, default values.

currency	
NFL	symbol for the costs
assembly	
30000. 1.005	c_c_1 sf
windfarm	
74. 3000. 1900.	c_c_1 c_c_2 c_c_3
safety_control	
8000. 10000 3000 1.2 2.	c_c_1 c_c_2 c_c_3 sf_1 sf_2
hub	
8000. 2500. 1250.	c_c_1 c_c_2 c_c_3
drive_train	
900.	c_c_1
electrical_system	
0.25 25. 50. 48000. 65. 1	a b c c_c_1 c_c_2 ngen
nacelle	
6000. 1.375.	m_c_1 c_c_1
yaw_mechanisme	
6500.	c_c_1
tower	
4. 0.03 175. 2.1E+11 7800. 150.E+06 50.E+06 5. 240.E+06 0.8 1.25 0.8 1.25	NFL/kg. c_dia_tt c_buckling Esteel rho steel max allowable extreme stress [Pa] max allowable fatigue stress [Pa] m in S_N curve yield stress allowable constants for tower eigenfrequencies
blade	
25.0 5.0 0.0 1. .TRUE. 3.E+10 1900. 1600. 300.E+06 10 120.E+06 0.002 0.55	fl/kg c_c_2 cost of tip fl/kg c_mass sfcntr lbox true for box type construction else elliptical Espar [Pa] rho spar [kg/m^3] rho skin [kg/m^3] max allowable fatigue stress [Pa] m in S-N curve max allowable max stress [Pa] minimum skin thickness [m] Chord for strength over chord for aerodynamic prop.

Parametric Cost Functions

The parametric cost functions, described in [4], are component cost estimate functions based on the following general equation

$$ComponentCost = a \cdot (SizeQuantity)^{exponent}$$

which was initially derived from statistics of many components.
For each component it is important to determine the relevant *size quantity*, which can be e.g. the tower height or rotor diameter.
The cost are divided in

- **Factory costs**
- **Extra Factory costs**

The **Factory cost**s are component cost and assembly cost.
Cost function for the following components are developed:

- Rotor
- Gearbox
- Generator
- Power electronics
- Transformer
- Nacelle bedplate
- Hydraulics
- Control System
- Ventilation
- Primary shaft
- Bearings for the primary shaft
- Yaw bearing
- Full size brake
- Parking brake
- Tower Head
- Tower
- Miscellaneous

Extra Factory costs are cost made between the point where the wind turbine leaves the wind turbine manufacturer and the point where the turbine is producing electricity into the grid. These costs are divided into the following separate items

- Foundation
- Land
- Site Preparation
- Transportation
- Erection
- Electrical Connections
- Remote Control
- General Site Cost
- Engineering Cost

Below a summary of the cost models is given, which is copied integral, including equation numbers, from [4].

Rotor:

$$f1 = \left(\frac{C_T}{.65}\right)_{Rated}^{.5} \qquad \text{(3a)} \ldots \; if V_{Extreme} \leq 60 \; m/s$$

$$f2 = \left(\frac{V_{Extreme}}{60}\right)^{2} \qquad \text{(3b)} \ldots \; if V_{Extreme} > 60 \; m/s \text{ and fixed pitch blades then}$$

$$factor = \mathbf{MAX}(f1, f2)$$

$$C_{rotor} = 120 \cdot D^{2.32} \, n^{-0.234} \cdot factor \qquad (5)$$

Where *n* is the total number of blades manufactured, divided by the number of blades in the rotor.

Gear Box:

$$C_{\text{gear}} = 1.28(Q,Nm)^{0.943} n^{-0.152} \qquad (6)$$

Standard Generator:

Solve *n* from:

$${}^{10}\boldsymbol{Log}(n) = 7\text{-}0.7\cdot{}^{10}\boldsymbol{Log}(P,kW)\text{-}.0115\cdot\{{}^{10}\boldsymbol{Log}(P,kW)\}^{5} \qquad (7)$$

then use in:

$$C_{stdGenerator} = 1700 k_{Type} k_{Enclosure}(\text{P,kW})^{0.6} n^{-.074} \qquad (8)$$

Where

k_{Type} =0 .75(asynch) …=1.0(synch)

$k_{Enclosure}$ = 1.0(basic open) .. = 1.8 (enclosed/protected)

T = 0.95

Direct Drive Generator:

$$C_{DirDriveGen}=2520(P,kW)^{0.85} n^{-.0152}(1.091+0.303\cdot{}^{10}\mathbf{log}(P,kW)) \qquad (13)$$

Power Electronics:

$$C_{PowerElectronics} = k_{PE}\cdot(P,kW)^{0.6}\cdot n^{-epe} \qquad (14)$$

where *n* is assumed to be equal to the number of rotors The other parameters are defined as

Parameter	Synch.	Asynch.
k_{PE}	1600	4800
Epe	0.074	0.234

Transformer:

$$C_{Transf} = \{4500+0.017\cdot(P_{Transf},kW)\} n_{Transf}^{-0.074} \qquad (15)$$

where the power figure may or may not be equal to the power of one turbine. The idea is that one transformer in principle can be used for a group of turbines. It is therefore a good idea to separate both power and number of units from those of the turbines.

Nacelle Bedplate:

$$C_{Bedplate} = 63.9\cdot(Q,Nm)^{0.638} n^{-0.234} \qquad (16)$$

Hydraulics:

$$C_{Hydr} = 52.9\cdot \text{D}^{2.32} n^{-0.234} \qquad (17)$$

Control system:

$$C_{control} = 30000 + 150000/n + 18000 n^{-0.4283} \qquad (19)$$

Ventilation:

$$C_{Ventilation} = 14\cdot(P,kW) \qquad (20)$$

Primary shaft:

$C_{MainShaft} = 16D^{2.32}n^{-0.152}$ (21)

Bearings for the Primary Shaft:

$C_{BearingShaft} = 110000T^{0.1}n^{-0.152}$ (22)

Yaw Bearings:

$C_{YawBearing} = 3.06D^{2.32}n^{-1.52}$ (23)

Full Size Brake:

$J_{Rotor} = 0.095 \cdot (numberOfBlades) \cdot \left(\frac{D}{2}\right)^{4.7}$ …. based on (24)

Use

$\omega_{Design} = 100 / R$ meaning that brake is applied at a tip speed of 100 m/s.

$m_{brakeSystem} = 0.0227 \frac{J_{Rotor}\omega^2{}_{Design}}{T_{Disk} - 35}$ (29) and (30)

$C_{FullBrake} = 60 \cdot m_{brakeSystem}n^{-0.2345}$ (31) and (32)

Parking Brake:

$C_{parkingBrake} = 4.4D^2n^{-0.152}$ (33) and (35)

Tower Head:

$W_H = \mathrm{a_h} \cdot D^{2.7}$ (35)

where

$a_h = 0.5$ … extremely light
$a_h = 1.0$ … normal
$a_h = 2.0$ … extremely heavy

Tower:

Operating conditions:
A separation between types must be made.
Pitch controlled turbine:
If not known use CT=0.65 together with rated wind speed V, insert in (45) and continue.
Stall controlled turbine:
If the rotor design thrust coefficient is known continue using V= cutout wind speed with (45). If also the thrust is known go directly to the step following Eq. (45) below.

$\lambda = V_{Tip}/V$ (38)

$\lambda_{Equivalent} = \frac{\lambda}{1 - 0.27(n_B - 2)}$ (39)

$x = \lambda_{Equivalent}/8$ (40)

$y_1 = CD_{90} \cdot S$ (41)

$$y_2 = 0.5\left(1+\frac{x}{1.75}\right) \quad (42)$$

$$a = 2^{-\left(\frac{x}{.69}\right)^{2.5}} \quad (43)$$

$C_T = a \cdot y_1 + (1-a) y_2$ (44)

$$T_R = \frac{1}{2}\rho\pi R^2 C_T V^2 \quad (45)$$

In case of a cylindrical tower use TR = 1.0 in the following expression.

$\Delta h = 0.04D$ … an estimate of the distance from the tower top to the main shaft.

$$T_T = C_{Dt}\rho V^2 r_{Root}(h+2\Delta h)\left(\frac{1}{2(\alpha+1)} - \frac{1-TR}{2\alpha+3}\right)$$ (50) … slightly modified.

$M_O = (h + \Delta h) \cdot (T_T + T_R)$ (52) … modified … operating conditions

Extreme wind conditions:

$$T_R = \frac{1}{2}\rho\pi R^2 CD_{90} \cdot S \cdot V_E^2$$ (45) … modified

If the machine has pitch mechanism and/or is free to yaw T_R can probably be ignored (or use 10% of it).

$$T_T = C_{Dt}\rho V_E^2 r_{Root}(h+2\Delta h)\left(\frac{1}{2(\alpha+1)} - \frac{1-TR}{2\alpha+3}\right) \quad (50)$$

$M_E = (h + \Delta h) \cdot (T_T + T_R)$ (52) … modified … extreme conditions

$$r_{Root,O} = \sqrt[3]{\frac{M_O}{\pi f_r \sigma_{Des,OperatingCond}}}$$ (54) … modified.

Use a design stress number between 14.E6 and 20.E6 for operation.

$$r_{Root,E} = \sqrt[3]{\frac{M_E}{\pi f_r \sigma_{Des,ExtremeCond}}} \quad (54)$$

Use a design stress number of 400.E6 for the extreme wind case.

$r_{Root} = \max(r_{Root,O}, r_{Root,E})$

$\rho_{Fe} = 7800$ kg/m^3 (57)

Depending on choice of tower select from:

Constant radius tower:

$$W_T = \pi\rho_{Fe} \cdot r_{Root}^2 \cdot f_r \cdot h \cdot (1+TT) \text{ …constant radius tower} \quad (56)$$

Conical tower:

$$WT = \frac{2\pi}{3}\rho_{Fe} r_{Root}^2 \cdot f_r \cdot h \cdot (1+TR+TR^2) \text{ … conical} \quad (60)$$

The cost finally:

$$C_{Tower} = 5W_T \quad (61) \text{ … modified}$$

Miscellaneous:

$$C_{Misc} = 26.8D^{2.32} \quad (63)$$

$$C_{Assembly} = 0.05 \sum_{i=1,NC} C_i \quad (64)$$

where *i* symbolically refers to any of the cost items defined above.

Foundation:

M = **MAX**(M_E, M_O)

$W_{OG} = W_H + W_T$

Determine what the design factor *n* should be, use figure. 8, of [4]. Then iterate to get the tower foot radius using:

$$RF = \sqrt[3]{\frac{\frac{4M}{n \cdot g \cdot R_f} - W_{og}}{1382}} \quad (75)$$

Determine how much reinforcement is to be used in the casting. A typical number can be ε = 0.02.
Also consider necessity for piling.

Circumstances:	K_{piling}
Good firm ground	1.0
Good sand	1.2
Sand/clay 50/50	1.4
Clay	1.6
Severe clay cond.	2.0

$$Wf = 1382 \bullet R_f^3 \quad (74)$$

$$C_{Found} = k_{piling} \{0.123(1-\varepsilon)+3.33\varepsilon\} W_f \quad (76)$$

Land:

Determine k_{Land}, i.e. the cost of land per m^2.

$$A_{Land} = \mathbf{MAX}\{0.;3.82\cdot(DiskArea)-800\}\text{m}^2 \quad (77)$$

$$CLand = k_{Land} A_{Land} \quad (78)$$

Site Preparation:

Determine specific cost for road construction. Low: Graveled k_C = 30.

High Cement $k_C = 130$
L and w (length and width of road must be given in m).

$$C_{Site} = 5600+28.8L+k_C L\cdot w \qquad (79)$$

Transportation:

$$C_{Tpt} = (5.84\cdot D+400)\cdot(L,km)+0.486D^{2.64} \qquad (81)$$

Erection:

$$C_{Erect}=.93D^3 + \delta\cdot 26000. \qquad (82)$$

where δ=0 for 1 and 2 blades; δ=1 for 3 blades and more

Electrical Connections:

$$C_{Connect} = 165L \qquad (83)$$

where L is the length of the cable.

Remote control:

$$C_{Remote} = 16000 \qquad (84)$$

General Site Costs:

$$C_{General} = 5260D^{0.55} \qquad (85)$$

Engineering:

$$C_{Eng} = 2.6D^3 \qquad (86)$$

Total:

Sum of the above.

DEFINE.DEF, default values.

currency	NFL	
alfwsh	0.20000E+00	Wind shear profile parameter.
ah	0.10000E+01	Tower head weight factor.
cdt	0.50000E+00	Tower drag coefficient.
fr	0.10000E-01	Ratio tower wall thickness to radius.
Tt \#	0.50000E+00	Thickness taper of the tower wall (cylindrical twr).
tr	0.60000E+00	Tower diameter taper ratio (conical twr).
ntur	100	Number of wind turbine systems in the series
nrotor \# \#	100	Total number of blades from the series production divided by the number of blades on the rotor
Ptrans \#	0.48000E+06	Transformer nominal power, kW - can be for a whole group.
Ngen \#	5000	Total number of generators from the series production.
Ngear \#	600	Total number of gear boxes from the series production.
Typgen \# \#	1	-> StdSynch - 2 -> StdAsynch - 3 -> DirectDrive
Kenc \# \#	2	Generator enclosure. 1-> open 2-> enclosed.
Kbrake \# \#	1	Type of brake. 1-> Full torque 2-> Parking.
tdisk	0.28000E+03	Acceptable max brake disk temp., deg. C.
Kpiling \# \# \# \# \#	0.10000E+01	Piling cost factor on foundation. - Good firm ground 1.0 (no piling necessary) - Good sand 1.2 - Sand/clay 50/50 1.4 - Sand/clay 50/50 1.4 - Severe clay cond.2.0
nfound	0.60000E+00	Foundation design factor (0 < nFound < 1.0).
Eps \#	0.30000E-01	Weight of reinforcement div by the concrete mass in foundation
kland	0.70000E+02	Specific land cost, Hfl/m2.
kc	0.75000E+02	Specific road construction cost, Hfl/m2.
lrd	0.10000E+03	Length of road per turbine in the group, m.
wrd	0.50000E+01	Width of road, m.
kcable	165	Cost of power lines per m.
Lcable \#	0.80000E+02	Length of power cables per turbine in the group, m.
ltpt	0.20000E+03	Length transportation (plant to site), km.
mstrfa	170.E+06	maximum fatigue stress tower material N/m^2
mstrex	400.E+06	maximum static stress tower material N/m^2
smste	7.800E+03	densisty of tower material

Installation

System demands

The BLADOPT model can run under Windows95/98 or WindowsNT. The PC should have a Pentium-II processor or higher and at least 32 Mb memory.

Procedure

BLADOPT will be delivered on CDROM. Place CDROM in the drive and activate Setup.exe from the drive folder (most likely D:). Setup will install BLADOPT on your system.

Directories/files

After installation of BLADOPT the following files should be present on your system in the folder C:\Program Files\BLADOPT:

ui.exe	the BLADOPT program
usrman.hlp	online help file
st4unst.log	contains information for a proper removal of BLADOPT

Removal

The BLADOPT application can be removed by opening the icon *My Computer* on the desktop. In this window open the icon *Control Panel*. This will again open a window, which contains the icon *Add/Remove Programs*. Clicking this icon will show a dialogue box with a list of programs installed on your system. Select BLADOPT from the list and click the button Add/Remove… After clicking this button, the BLADOPT application will be removed from your system.

User Interface

Activating BLADOPT

Main window

The main window, see Figure10, gives you the possibility to adjust design parameters, start model calculations and view the model results. The window contains a number of tabs and menus that will be explained in the next paragraphs.

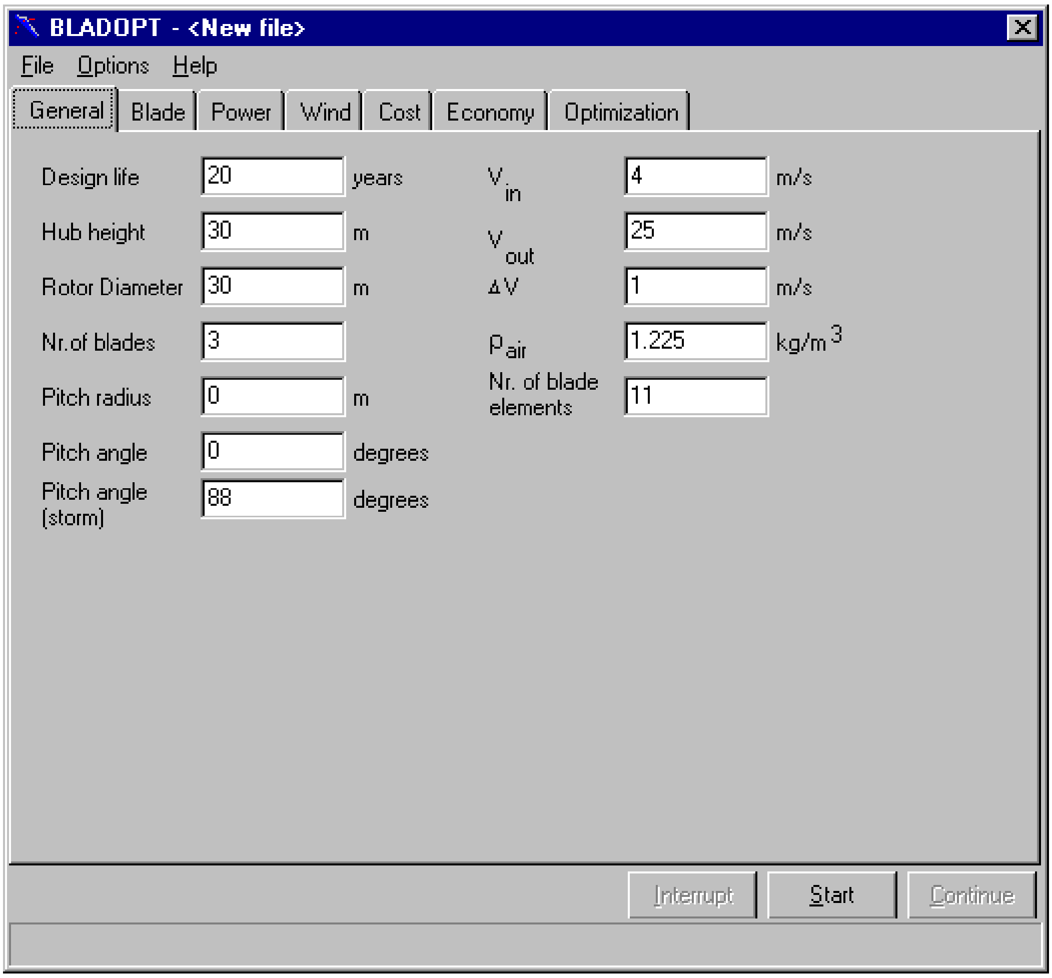

Figure10 the main window

Menu File

The File menu has several items. Depending on the state of the program one or more of these items cannot be selected (the gray ones).

New

Start a new design with default values for the design parameters.

Open…

Open an already existing design database.

Save

Save the current settings and model results in the current database.

Save as…

Save the current settings and model results in another database.

Close

Close the currently open design database.

Print

Print the results of the last function evaluation to a printer or to a file.

Exit

Close the currently open database and exit the program.

Menu Options

Graphics…

After clicking the menu item Graphics…, a new window appears (see Figure 19). In this window the values calculated by the BLADOPT model can be viewed as graphs. See also *Graph window*.
See also *Menu File*

Menu Help

Contents…

Selecting this window presents the on-line user manual.

About…

After selecting this item, a window with information about the program appears.

Button Interrupt

With this button it is possible to interrupt the calculations of the model. This button can only be pressed when the model is active. After pressing this button the model will finish the calculations for the current iteration and then halt the calculations. At that moment the Interrupt button will be disabled (grayed).
At this moment the *Continue* button will be enabled and you can modify the design parameters you like. Some design parameters however, if changed, force the model to restart the calculations. If you change such a parameter, the *Continue* button will be disabled.

Button Start

After pressing this button the model starts its calculations. By pressing the Interrupt button the calculations are interrupted.

Button Continue

After pressing this button the model continues its calculations with possibly modified parameters. Note that if parameters have been modified, which makes it impossible for the model to continue, this button will be disabled and you can only restart the model. The calculations can be interrupted again by pressing the Interrupt button

tab General

This tab, see Figure 10, contains the following text boxes to adjust general design parameters. The following parameters can be modified:

textboxes

Design life

N_{life}, the intended fatigue life (years) for the wind turbine. This parameter is only used to determine the number of load cycles due to turbulence and rotor rotations for the tower and rotor blade.
Allowable values: $0 \leq N_{life} \leq 1000$.
Changing this parameter will result in a restart with an empty database.

Hub height

H_{hub}, the height (m) of the rotor centre above ground level.
Allowable values: Drotor/2 ≤ 200.

Rotor diameter

D_{rotor}, the diameter of the rotor (m).
Allowable values: 5 ≤ 200.

Nr. of blades

N_{blade}, the number of rotor blades which make the rotor.
Allowable values: integers, $2 \leq N_{blade} \leq 4$.

Pitch radius

R_{pit}, radius (m) where a pitch bearing, if there is one, is positioned.
Allowable values: $0 \leq R_{pit} \leq D_{rotor}/2$.

Pitch angle

θ_0, Initial pitch angle (^{o}). For a stall regulated wind turbine this will be overruled by the power control algorithm. For a pitch controlled wind turbine the given pitch angle will be used below V_{rated}.
Allowable values: $-180 \leq \theta_0 \leq 180$.

Pitch angle (storm)

The pitch angle (^{o}) for load calculations at V_{storm} and rotor parked
Allowable values: $-180 \leq \theta_0 \leq 180$.

V_{in}

Cut in wind speed (m/s), at which the wind turbine is assumed to start.
Allowable values: $1 \leq V_{in} \leq V_{out}$.

V_{out}

Cut out wind speed (m/s), at which the wind turbine is assumed to stop.
Allowable values: $V_{out} <= 30$ m/s

ΔV

Wind speed interval (m/s) which is used in the aerodynamic analysis.
Allowable values: $\Delta V >= (2.* (V_{out} + 1) - 1)/127$

ρ_{air}

Density of the air, usually 1.225 kg/m^3 at ground level.
Allowable values: $0.5 \leq \rho_{air} \leq 1.5$

Nr. of blade elements

N_{elem}, the number of equally spaced elements in which the blade is divided between the rotor centre and the blade tip.
Allowable values: integer, $5 \leq N_{elem} \leq 20$

tab Blade

The Blade tab (see Figure 11) contains blade specific parameters.

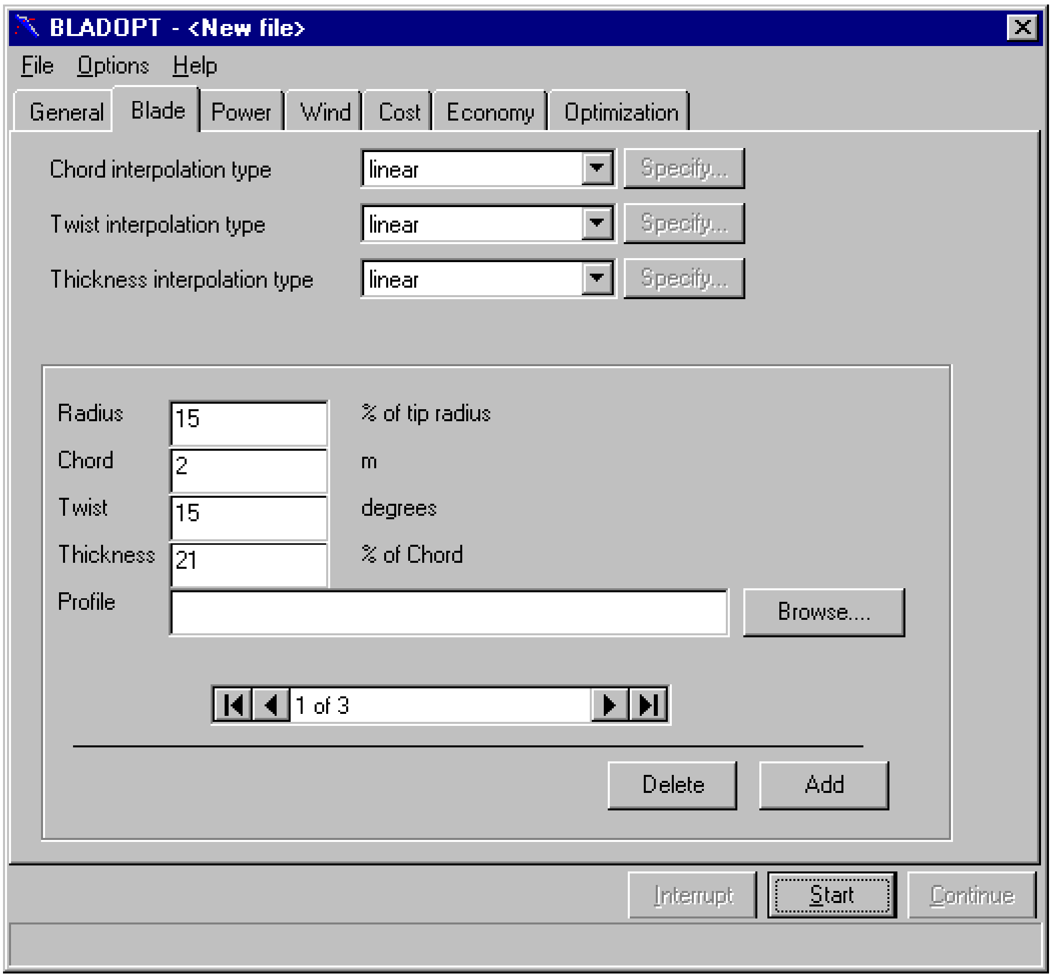

Figure 11 the blade definition window

listboxes

Chord, Twist, Thickness interpolation type

These list boxes let you select an interpolation type. Known types are:

- linear
- spline (not active)
- tension spline (not active)

The text boxes below are used to define a rotor blade. For each radial position indicated at least the number of the text boxes needs to be defined. For each item, chord, twist, thickness and profiles at least 2 radial positions have to be given see the blade definition of section Engineering cost, blade model.

text boxes

Radius
Span wise position, (%) of the tip radius.
Allowable values: $0 \leq \text{radius} \leq 100\%$

Chord
c(*r*), the width of the blade at span wise position *r* according to some aerodynamic convention.
Allowable values $0 < c(r) \leq 10.$ m

Twist
$\theta(r)$, the twist distribution of the blade, by definition the twist angle is zero at the tip radius.
Allowable values: $-180° \leq \theta(r) \leq 180°$, except at radius = 100 % where the twist equals 0° by definition

Thickness
t(*r*), the thickness distribution of the blade in % of the chord, only used in the cost function for the rotor blades.
Allowable values $0 \leq t(r) \leq 100\%$.

Profile
path and name of the file which contains the profile aerodynamic coefficients, cl, cd, and cm.
Format of the file(s) is explained in annex **A.** When at a certain radial position a profile is already defined while this is not the intention, one can delete the chosen profile by selecting the profile and use the delete key.

data control (1 of ..)
The data control (see Figure 12) enables you to step through all blade specifications.

Figure 12

With the most left button one jumps to the first blade specification, and with the most right button to the last. The inner button enables a single step back or forward.

button Specify…
When clicking this button a window appears which lets you modify the coefficients for the selected interpolation type. Linear only (other interpolation type are not implemented)

button Browse…
After clicking this button a standard file selection window appears which enables you to search for and select a profile file.

button Delete
Deletes the current blade specification, unless the pointer is in the profile box which enables the deleting of the profile information

button Add
Adds a new radial position for the blade specification

tab Power
In this tab (see Figure 13) it is possible to modify power related design parameters.

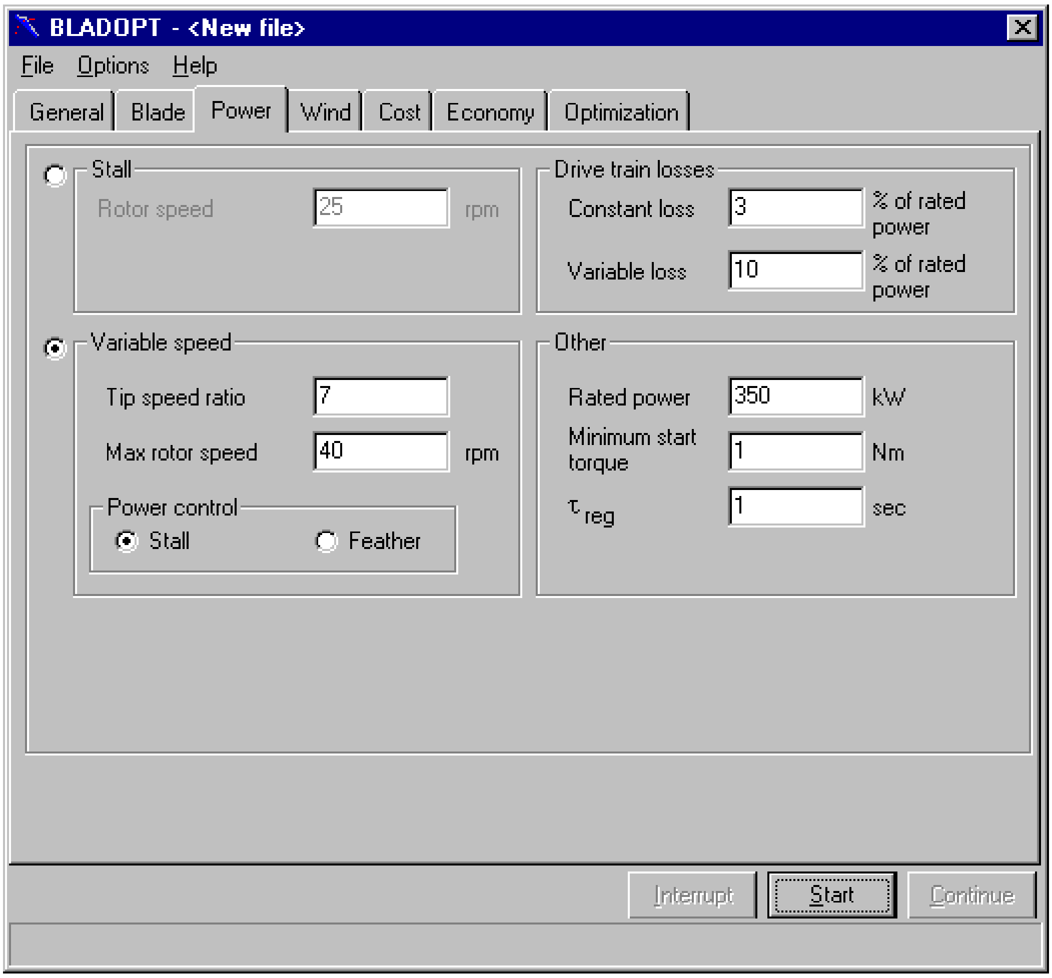

Figure 13 the power control window

radiobuttons

Stall | Variable speed
These toggle buttons indicate whether the turbine is a constant speed stall controlled wind turbine or a variable speed (pitch) controlled wind turbine.

radiobuttons

Stall | Feather
These toggle buttons indicate the power control for a variable speed wind turbine above V_{rated} , i.e.pitching to stall or pitching to feather.

Text boxes

Rotor speed

For a stall controlled constant speed wind turbine the rotor speed in rotations per minute.
Allowable values: $1 \leq rpm \leq 100$.

Tip speed ratio

Tip speed ratio (λ) is the ratio between the speed of the tip of the rotor blade in the rotation plain and the wind speed. For optimum energy yield this ratio is kept constant below rated power for a variable speed wind turbine.
Allowable values: $1. \leq \lambda$.

Max rotor speed

Due to alleviation of the axial force on the tower head it is possible to reduce the maximum rotor speed (rpm_{max}) already below V_{rated}. Another usage or application of this control can be to minimise the cost of the pitch control system due to the fact that the maximum pitch speed needed can be reduced.
Allowable values: $1 \leq rpm_{max}$.

Constant loss

Loss in the drive train (C_{loss}), the part which is not depending on the power transmitted, given as a percentage of the rated power.
Allowable values: $0 \leq C_{loss} + V_{loss} \leq 100\%$.

Variable loss

Loss in the drive train (V_{loss}), the part which is depending on the power transmitted, given as a percentage of the rated power.
Allowable values: $0. \leq Vloss + C_{loss} \leq 100\%$.

Rated power

The maximum power (P_{rated}) the components of the wind turbine are designed for.
Allowable values: $0 \leq P_{rated}$.

Minimum start torque

An optional constraint, $Torque_{start}$ for the optimisation process, the start torque at $V_{cut\ in}$.
Allowable values: $0 \leq Torque_{start}$.

τ_{reg}

Time constants, indicating the speed of the pitch controller in seconds, see section *Load Model*. This parameter is used to determine whether the pitch control unit is fast enough to alleviate the load due to gusts.

tab Wind

The wind tab (see Figure 14) contains the wind related design parameters.

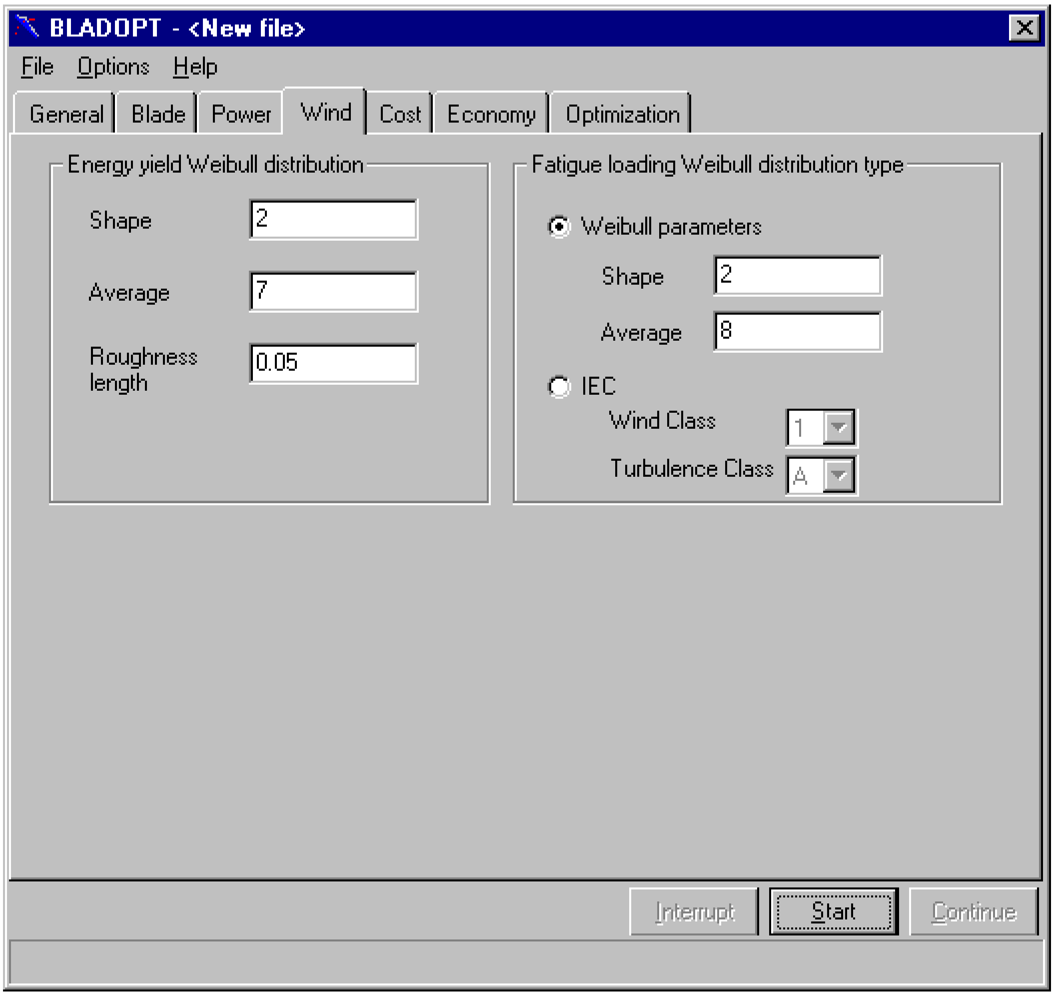

Figure 14 the wind control window

radiobuttons

Weibull parameters | IEC Wind Class

These toggle buttons indicate whether the wind speed distribution for the load spectrum calculations should be based on an IEC wind class or a user defined wind speed distribution.

listboxes

IEC Wind Class

Here the IEC wind class (1-4) can be defined.

textboxes

Shape (Energy yield Weibull distribution)

The shape factor of the Weibull wind speed distribution for the energy production (wse).
Allowable value: 1 < wse< 10.

Average (Energy yield Weibull distribution)

The average wind speed for the Weibull wind speed distribution for the energy production (vae).
Allowable values: 1 ≤vae< 25 ms/

Shape (Fatigue loading Weibull distribution type)

The shape factor of the Weibull wind speed distribution for the fatigue load spectrum (wsf). Allowable values: $1 < wsf < 10$

Average (Fatigue loading Weibull distribution type)

The average wind speed for the Weibull wind speed distribution for the fatigue load spectrum (vaf). Allowable values: $1 \leq vaf < 25$ m/s

tab Cost

This tab (see 15) contains the cost related design parameters.

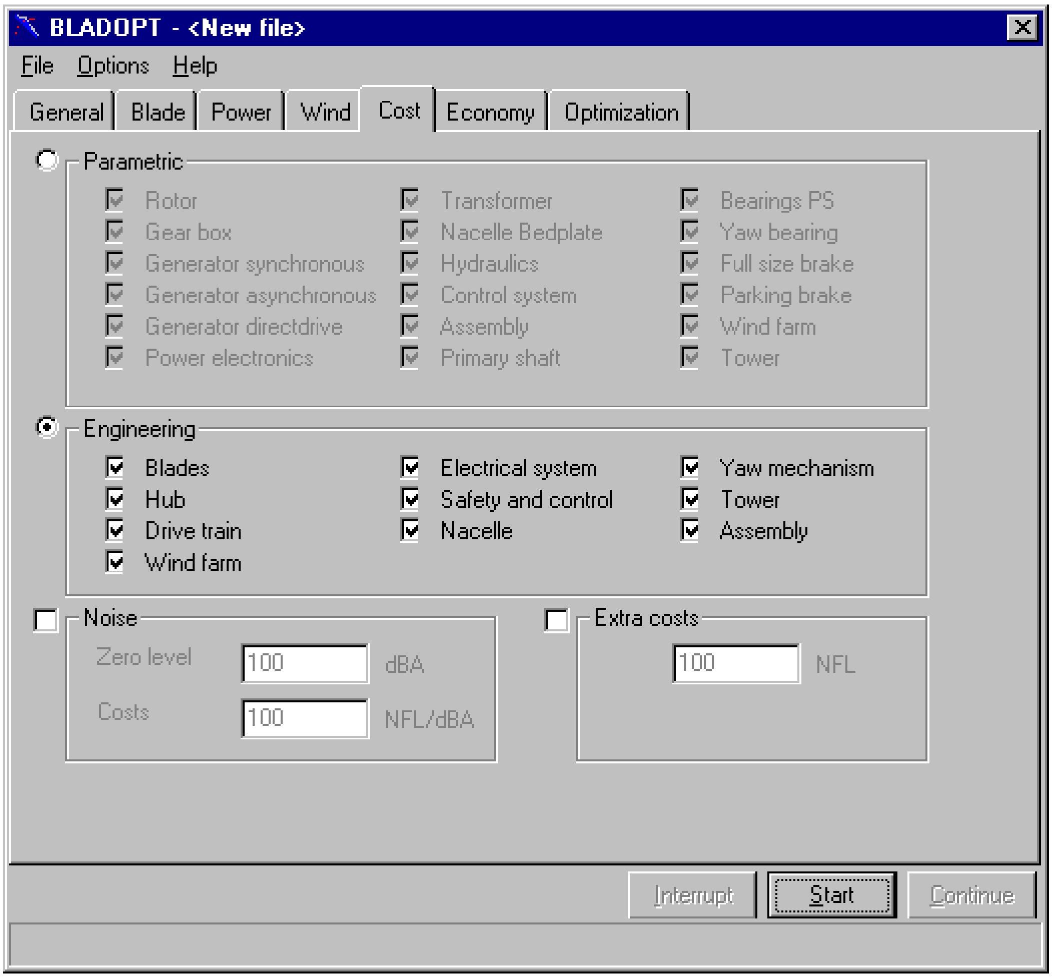

Figure 15 the cost function control window

radiobuttons

Parametric | Engineering

Toggle to choose parametric or engineering cost functions. See [3,4].

checkboxes

The parametric costs which can be (de) selected are:

Rotor
Rotor cost function included in analysis when active.

Gear box
Gearbox cost function included in analysis when active.

Generator synchronous
Synchronous generator cost function included in analysis when active.

Generator asynchronous
Asynchronous generator cost function included in analysis when active.

Generator direct drive
Direct drive cost function included in analysis when active.

Power electronics
Power electronics cost function included in analysis when active.

Transformer
Transformer cost function included in analysis when active.

Nacelle bed plate
Nacelle bed plate cost function included in analysis when active.

Hydraulics
Hydraulics cost function included in analysis when active.

Control system
Control system cost function included in analysis when active.

Ventilation
Ventilation cost function included in analysis when active.

Primary shaft
Primary shaft cost function included in analysis when active.

Bearing PS
Bearing primary shaft cost function included in analysis when active.

Yaw bearing
Yaw bearing cost function included in analysis when active.

Full size brake
Full size brake cost function included in analysis when active.

Parking brake
Parking brake cost function included in analysis when active.

Wind farm
Windfarm cost included in analysis when active

Tower
Tower cost function included in analysis when active.

The engineering costs which can be (de) selected are:

Blades
Blades cost function included in analysis when active.

Hub
Hub cost function included in analysis when active.

Drive train
Drive train cost function included in analysis when active.

Wind farm
Wind farm cost function included in analysis when active.

Electrical system
Electrical system cost function included in analysis when active.

Safety and control
Safety and control cost function included in analysis when active.

Nacelle
Nacelle cost function included in analysis when active.

Yaw mechanism
Yaw mechanism cost function included in analysis when active.

Tower
Tower cost function included in analysis when active.

Assembly
Assembly cost function included in analysis when active.

The other check boxes are:

Noise
The aerodynamic noise will be calculated and the cost per dBA above the zero noise level will be included in the total cost of the wind turbine when active.

Extra costs
Extra cost of the turbine, indicated in the box Extra Cost, compensating for cost not yet included in the parametric/engineering cost, will be included in the total cost of the wind turbine when active.

textboxes

Noise Zero level
The noise level below which no extra cost is taken into account for the total turbine cost.
Allowable values: ≥ 0.

Noise costs
The cost in \$/dBA for the calculated noise level above the noise zero level.
Allowable values: ≥ 0.

Extra costs

The extra costs to be added to the calculated total cost for the wind turbine when the extra cost button is active.
Allowable values: ≥ 0.

tab Economy

The Economy tab (see Figure 16) contains the economy related design parameters.

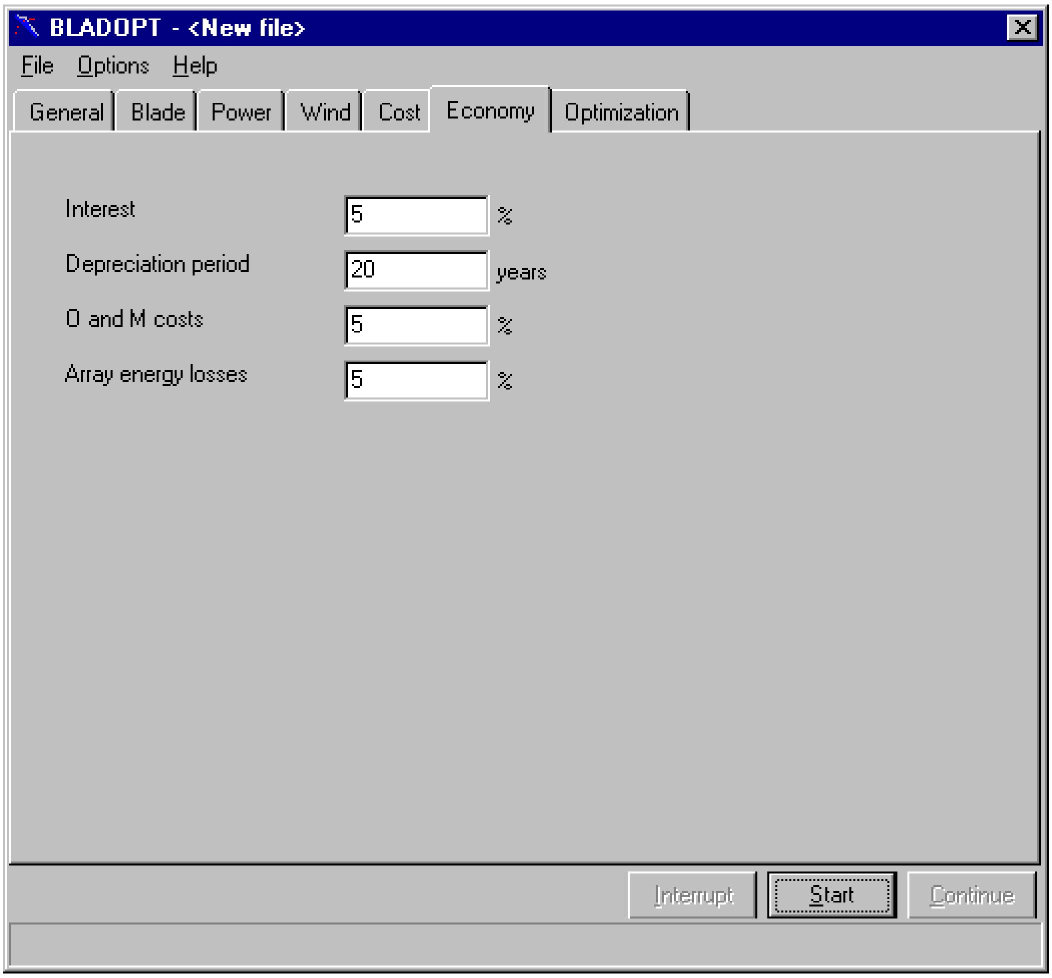

Figure 16 the economy control window

textboxes

Interest

The interest rate, used to determine the annual cost of the wind turbine in %. The user can possibly correct this value for the assumed inflation rate.
Allowable values: ≥ 0

Depreciation period

Economic life time, in years, of the wind turbine, usually shorter than the technical lifetime.
Allowable values: ≥ 0

O and M costs
Operating and maintenance cost, as a percentage of the total cost of the wind turbine.
Allowable value ≥ 0

Array energy losses
Factor used to decrease the energy yield due to wind farm operation, wake losses, or assumed down time of the wind turbine.
Allowable values: ≥ 0

When the price performance is the target this can be achieved by setting the interest on rate on zero, the depreciation period on 9999 and the O&M cost and array energy losses to zero.

tab Optimisation
In this tab (see Figure 17) the design parameters which must be optimised can be selected. Constraints and step sizes can be set.

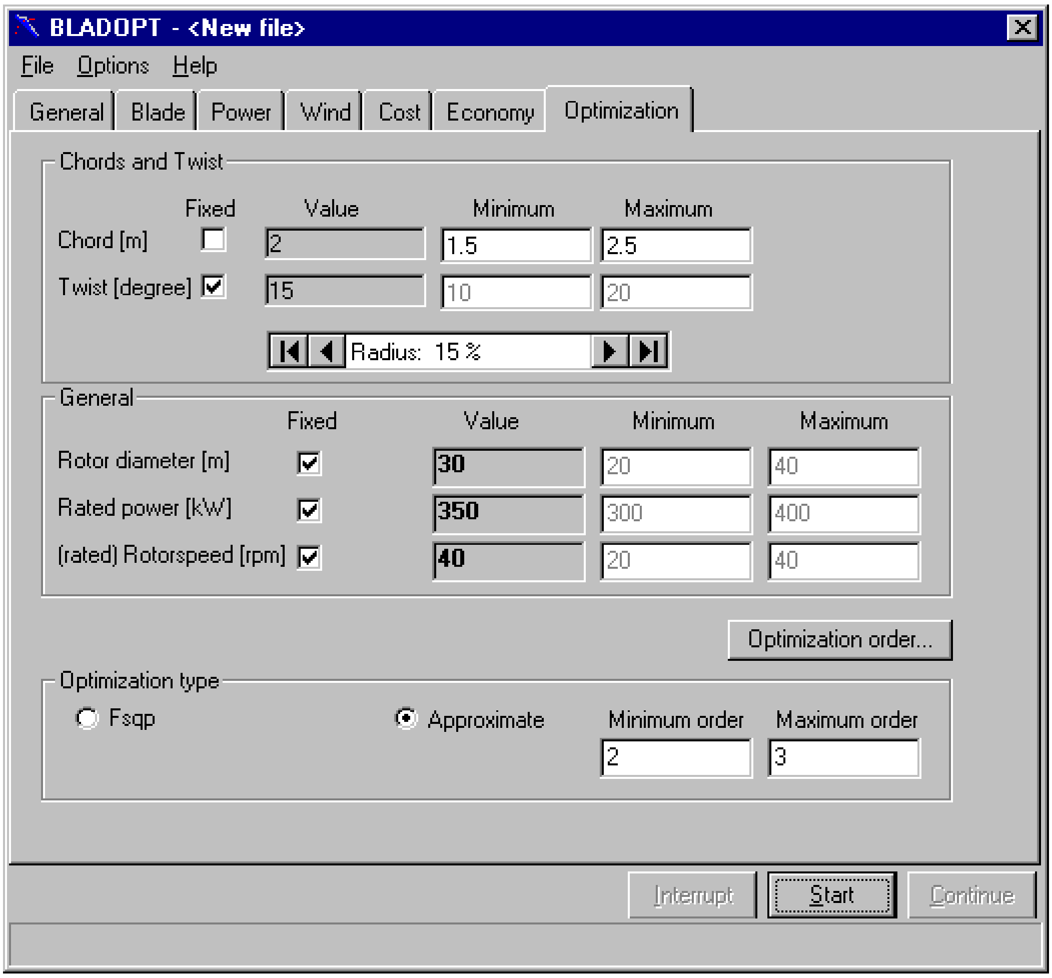

Figure 17 the optimisation control window

buttons

Optimisation order
After pressing this button a new window *Optimisation order* appears.

radiobuttons

Fsqp | Approximate

Toggle to choose between two different optimisation algorithms. The fsqp method is a zero order method, the approximate stands for an optimisation scheme based on a Feasible Sequential Quadratic Programming algorithm which searches for a minimum in an approximate model.

checkboxes

Chord Fixed

This button indicates whether the chord, entered by the user in the tab Blade, at a certain span wise position is free for optimisation. If the chord is allowed to be optimised it is necessary to enter the side constraints, the minimum and maximum values.

Twist Fixed

This button indicates whether the twist, entered by the user in the tab Blade, at a certain span wise position is free for optimisation. If the twist is allowed to be optimised it is necessary to enter the side constraints, the minimum and maximum values.

Rotor diameter Fixed

This button indicates whether the rotor diameter is to be optimised, the rotor diameter and rated power should not be optimised together.

Rated power Fixed

This button indicates whether the rated power is to be optimised, the rotor diameter and rated power should not be optimised together.

(rated) Rotor speed Fixed

This button indicates whether the rotor speed is to be optimised. For constant speed wind turbines the constant speed rpm is optimised, for variable speed wind turbines the maximum rotor speed will be optimised, although the maximum rotor speed will not be increased above rotor speed which yields rated power.

textboxes

Chord Value

This box indicates the actual value of the chord, at a certain span wise position, before the optimisation is started it shows the entered value in the tab Blade and during the optimisation it shows the value determined by the optimisation procedure.

Chord Minimum

For each span wise position where the chord is to be optimised a minimum value has to be entered. By default it is put at 0. m.

Chord Maximum

For each span wise position where the chord is to be optimised a maximum value has to be entered. No default values are available. If no maximum can be given enter a large number e.g. 25 m. However, it is always faster and safer to enter a realistic value.

Chord Start step size

The step size, to be entered here is used in the optimisation procedure to indicate the length of the variations for each optimisation parameter. By default 1% of the interval between maximum and minimum chord is used.

Twist Value

This box indicates the actual value of the twist, at a certain span wise position. Before the optimisation is started it shows the entered value in the tab Blade and during the optimisation it shows the value determined by the optimisation procedure.

Twist Minimum

For each span wise position where the twist is to be optimised, this can not be the tip chord, a minimum value has to be entered.
Allowable values: $-180^o \leq \theta(x) \leq 180°$, remember θ (100%) = 0.

Twist Maximum

For each span wise position where the twist is to be optimised a maximum value has to be entered. No default values are available. If no maximum can be given enter a large number e.g. 25 m. However it is always faster and safer to enter a realistic value.
Allowable values $-180^{\circ} \leq \theta(x) \leq 180^{\circ}$, θ(100%) = 0.

Rotor diameter Value

This box indicates the actual value of the rotor diameter, before the optimisation is started it shows the entered value in the tab General and during the optimisation it shows the value determined by the optimisation procedure.

Rotor diameter Minimum

When the rotor diameter is to be optimised a minimum value has to be entered. If no minimum can be given enter a small number e.g. 1 m. However it is always faster and safer to enter a realistic value.

Rotor diameter Maximum

When the rotor diameter is to be optimised a maximum value has to be entered. If no maximum can be given enter a large number e.g. 100. m. However it is always faster and safer to enter a realistic value.

Rated power Value

This box indicates the actual value of the rated power. Before the optimisation is started it shows the entered value in the tab Power and during the optimisation it shows the value determined by the optimisation procedure.

Rated power Minimum

When the rated power is to be optimised a minimum value has to be entered. If no minimum can be given enter a small number e.g. 10 kW. However, it is always faster and safer to enter a realistic value.

Rated power Maximum

When the rated power is to be optimised a maximum value has to be entered. If no maximum can be given enter a large number e.g. 10.E+03 kW. However it is always faster and safer to enter a realistic value.

(rated) Rotor speed Value

This box indicates the actual value of the (rated) rotor speed, before the optimisation is started it shows the entered value in the tab Power and during the optimisation it shows the value determined by the optimisation procedure.

(rated) Rotorspeed Minimum

When the (rated) rotor speed is to be optimised a minimum value has to be entered. If no minimum can be given enter a small number e.g. 1 RPM. However, it is always faster and safer to enter a realistic value.

(rated) Rotorspeed Maximum

When the (rated) rotor speed is to be optimised a maximum value has to be entered. If no maximum can be given enter a large number e.g. 100 rpm. However it is always faster and safer to enter a realistic value.

Minimum order
Parameter used when the approximate toggle is active. The minimum order for an approximate model: an approximate model of the first order is the lowest sensible value.
Allowable values: integer, ≥ 1.

Maximum order
Parameter used when the approximate toggle is active. The maximum order for an approximate model: an approximate model of the second or third order is probably the most sensible value, however up to the fourth order is allowed.
Allowable values: integer, ≤ 4.

Optimisation order window
This window (see Figure 18) enables you to change the order in which the specified design parameters should be optimised. For a well defined problem without many local minima the order will not influece the outcome, however in real problems the order will always influence the outcome. That is why it is sensible to change the order and/or the start design.

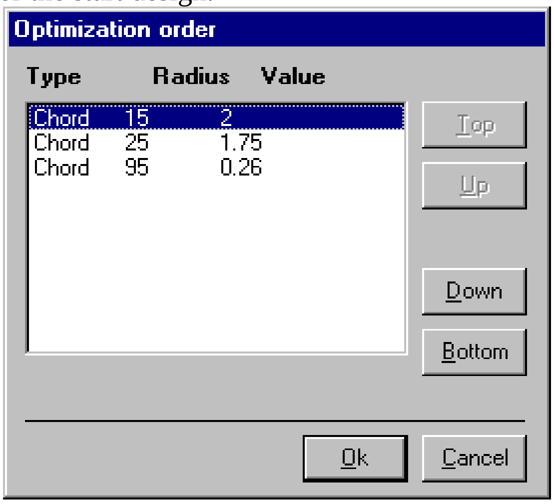

Figure 18 Optimisation order window

buttons

Top
After pressing this button the item selected in the list box is moved to the top of the list, i.e. it is the first to be optimised.

Up
After pressing this button the item selected in the list box is moved one place up in the list.

Down
After pressing this button the item selected in the list box is moved one place down in the list.

Bottom
After pressing this button the item selected in the list box is moved to the bottom of the list, i.e. it is the last to be optimised.

listbox

The list box displays all specified chords and twists in the specified order. You can select one chord or twist and move it up (with the Up button) or down (with the Down button) the list to the desired position. Use the Top button to place the selected item on top of the list, use the Bottom button to place it at the bottom.

Graph window

In the Graph window, the results of the model calculations are displayed in graphs. With the Graphs menu, you can select/deselect the graphs, or print the active graph.

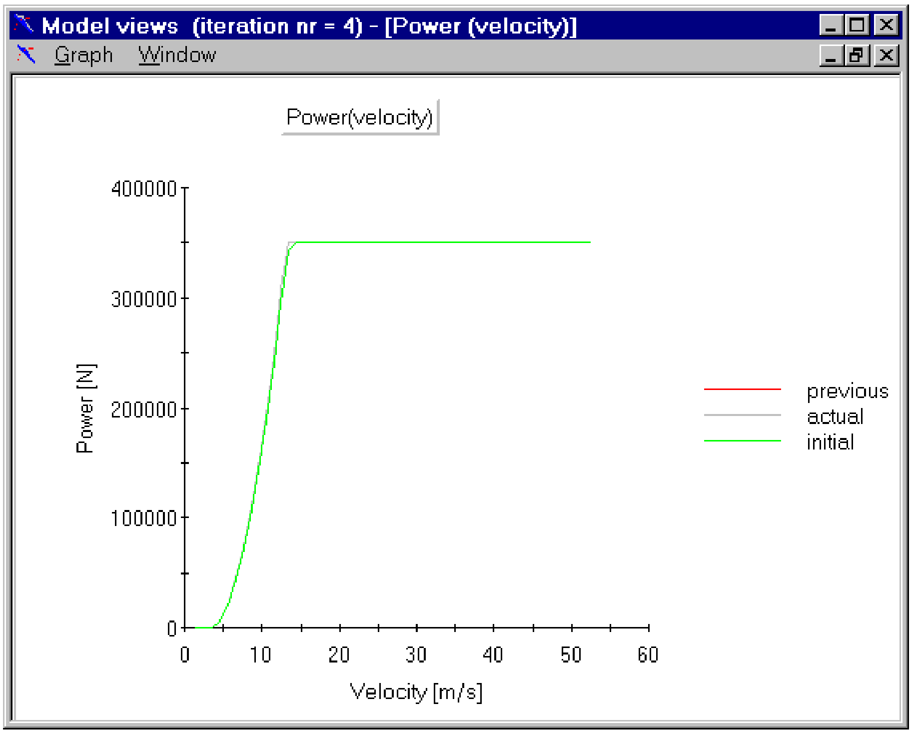

Figure 19 a graph window

Menu Graph

The Graph menu lets you select and deselect graphs, and make a printout of the active graph.

Power(velocity)

Electrical power versus wind speed graph.

Torque(velocity)

Torque versus wind speed graph.

Tipangle(velocity)

Tip angle θ versus wind speed for pitch controlled wind turbines.

Chord(radius)

Chord distribution graph, the 0^{th} , previous and last iteration chord distribution graph.

Twist(radius)

Twist distributions graph, the 0^{th} , previous and last iteration chord distribution graph.

kWh/year(iteration)
The energy yield versus iteration number graph.

$/kWh(iteration)
The COE versus iteration graph, the actual objective of the program.

dBA(iteration)
The aerodynamic noise versus iteration graph.

Axial Force(iteration)
The fatigue equivalent axial tower force versus iteration graph.

Diameter(iteration)
The rotor diameter versus iteration graph. Only useful when the rotor diameter is optimised.

Rotorspeed(iteration)
The fatigue equivalent axial tower force versus iteration graph. Only useful when the rotor speed is optimised.

Print…
selecting the Print… item enables you to print the active (selected) graph.

Menu Window
This menu has a number of items to (re)arrange the graphs.

Cascade
The open graphs will be overlapping each other but their titles are visible. Only the top-most graph is visible.

Tile Horizontal
The open graphs are placed under each other.

Tile Vertical
The open graphs are placed next to each other.

Arrange Icons
The iconified graphs are arranged along the lower portion of the Graph-window.

References

1	Bulder B.H.	Design Optimisation for wind turbines; Optimisation algorithms a state of the art study. ECN-C—96-030
2	Schepers J.G.	PVOpt: theory and test cases. ECN-C---96057
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4	Montgomery Jenssen B.O.G.	A simple parametric cost estimate method for horizontal axis wind turbines. ECN–C–96-031
5	Bartels R.H.	Least Square fitting using orthogonal multinomials; ACM transactions on Mathematical Software, Vol. 11 No.3 Sept. 1985
6	Powell M.J.D.	An efficient method of finding the minimum of a function of several variables without calculating derivatives; The computer Journal, 1968
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8	Zhou J.L. Tits A.L.	An SQP algorithm for finely discretized continuous minimax problems and other minimax problems with many objective functions. SIAM Journal on Optimisation, 1996.
9	Wieringa J. Rijkoort P.J.	Windklimaat van Nederland
10	Tande O.J. Et.al.	IEA Recommended Practices for Wind Turbine Testing and Evaluation 2. Estimation of cost of energy from wind energy conversion systems

Annex; File formats

Profile files

The file(s) containing the profile characteristic should be conform the following format: The file can have any name however the extension should be **.prf**. The file contains upto 128 lines with 4 items per line. On each line the following parameters should be given:

$$\alpha_i \quad cl_i \quad cd_i \quad cm_i$$

In which α_i is the inflow angle
Cl_i is the 2 dimensional lift coefficient.
cd_i is the 2 dimensional drag coefficient
cm_i is the 2 dimensional moment coefficient

To indicate that no more lines should be read, a line with 4 zeros should be added. Behind the line with the 4 zeros, the program will not read any line. Files with more than 128 data lines will result in an error message. The data given should expand from 0° to 360°

Default cost data

There are two different kind of cost data files, the **defins.def** and the **define.def**. The **defins.def** contains the engineering/price constants/coefficients for the engineering cost model and the **define.def** file contains the engineering/price constants/coefficients for the parameteric cost model. The files are shown in the appropriate sections.

Annex; Cost Module Include Files

INCLUDE assembly.i

```
C
CM    Cost price data assembly for Engcost
C
CM    c_c_1   cost price coefficient                  [m^-2.5]
CM    sf      service factor                    [-]
C
CM    ascost      assembly cost                       [fl]
C
      REAL c_c_1
      REAL sf

      COMMON/assmbly/sf,c_c_1
```

INCLUDE blades.i

```
C
CM    cost price data of the blades of the optimum turbine for Engcost
C
CM    c_c_1 blade cost coefficient              [fl/kg]
CM    c_c_2 tip cost coeffient                  [fl/kg]
CM    c_mass      coefficient of mass of tip          [-]
CM    sfcntr      safety factor for control           [-]
CM    so    southwell coefficient               [-]
CM    lbox  logical wheter cross section is box
CM          or elliptical                       [-]
CM    espar elasticity modules spar             [N/m^2]
CM    smspar      density of spar material            [kg/m^3]
CM    smskin      density of skin material            [kg/m^3]
CM    mstrfa      maximum allowable fatigue stress    [N/m^2]
CM    mstrex      maximum allowable extreme stress    [N/m^2]
CM    mspar -1/m is the slope of the S-N line   [-]
CM    skin_t      minimum skin thickness              [m]
CM    csoverca
CM          ratio between stiffnes chord/aero chord [-]                 [m]
C
      REAL    c_c_1,c_c_2,c_mass,sfcntr,so,espar,
     &        smspar,smskin,mstrfa,mstrex,skin_t,csoverca

      LOGICAL lbox

      COMMON/blads/c_c_1,c_c_2,c_mass,sfcntr,so,espar,skin_t,
     &              smspar,smskin,mstrfa,mstrex,lbox,csoverca
```

INCLUDE bladprop.i

```
C
CM    Design data of the blades of the optimum turbine
C
CM    wx(0:nelmax)      resistance moment flatwise    [m^3]
CM    wy(0:nelmax)      resistance moment edgewise    [m^3]
CM    mass(0:nelmax)    mass of element               [kg]
CM    b(i)        spar width (breadth)          [m]
CM    h(i)        spar heigth             [m]
CM    skin(i)           mass of skin at position i    [kg]
CM    t(i)        blade thickness               [m]
CM    bladmas           total blade mass        [kg]
CM    fnr         blade eigenfrequency non rot. [rad/s]
CM    fr          blade eigenfrequency rotating [rad/s]
C
      REAL    wx(0:nelmax),wy(0:nelmax),mass(0:nelmax),
     &        b(0:nelmax),h(0:nelmax),skin(0:nelmax),t(0:nelmax)
      REAL    bladmas,fnr,fr

      COMMON /bladprop /bladmas,fnr,fr,wx,wy,mass,b,h,t,skin
```

INCLUDE constant.i

```
C
CM    constants to be used throughout the program
C
CM    g     gravitational constant                   [m/s^2]
CM    pi    goniometric constant pi=atan2(1.,1.)           [-]
CM    twopi goniometric constant equal 2 * pi         [-]
CM    conrad      conversion from degree to radials pi/180.       [-]
CM    arcsma      architecture depending smallest Real*8          [-]
C
      REAL  g
      DATA  g     / 9.80665 /

      REAL    pi,conrad,twopi

      REAL*8  arcsma

      COMMON /consta/ arcsma,conrad,pi,twopi
```

INCLUDE control.i

```
C234567890123456789012345678901234567890123456789012345678901234567890123456789012
C
CM    lvarsp      true for variable speed turbines
CM          above rated power                   [-]
CM    lambda      tip speed ratio below maxrpm or below Prated    [-]
CM    rpmmax      maximum rotational speed in rpm for variable
CM          speed wind turbine                        [rpm]
CM    rpmmin      minimum rotational speed in rpm for variable
CM          speed wind turbine                        [rpm]
CM    rpms  rotor speed constant speed wind turbine         [rpm]
C
CM    lpitch      true for pitch regulated, false for stall
CM          controlled                          [-]
CM    ltip  true for part span pitch control          [-]
CM    pitnor      normal pitch angle below vrated                 [deg]
CM    pitsto      pitch angle during stand still e.g. due to storm[deg]
C
CM    tau   pitch control time constant               [s]
C
CM    lstall  true for pitching to stall above rated power  [-]
CM    lequil      true when equilibrium curves have to be determined
CM    lteet true when rotor is teetered
C
CM    freq_t      tower frequency, for variable speed system should
CM          be avoided for rotor speed                [rad/s]
C
      REAL     lambda,rpmmax,rpmmin,rpms,tau,pitnor,pitsto,
     &         freq_t
      LOGICAL  lvarsp,lpitch,lstall,lequil,lteet,ltip

      COMMON /contrl/ lvarsp,lpitch,tau,lambda,lstall,
     &                rpmmax,rpmmin,rpms,freq_t,
     &                lequil,pitnor,pitsto,lteet,ltip
```

INCLUDE dritra.i

```
C
CM    cost price data of the drive train for Engcost
C
CM    c_c_1   cost price coef.                  [fl/kNm]
CM    sf    service factor of                   [-]
C
      REAL    c_c_1

      COMMON/dritrn/c_c_1
```

INCLUDE elemen.i

```
C
CM    blade element data for aero model and Engcost
C
C  *********************************************************************
C     s(0:nelmax) : values of s (along span) at sections,
C                 s(0) = 0.
C     chord(o:nelmax)   : values of chord at sections s(i), not de-
C                 fined at s(0)
C     twist(0:nelmax)   : values of twistangle at sections s(i),
C                 interpolated from tetapi from geodat.
C     thckns(0:nelmax): values of profile thickness at section s(i),
C                 interpolated from tetapi from geodat.
C     blroot            : s value at which aerodynamic blade root
C                 is defined, not necessarily co-incident
C                 with a s(i) value
C     rootch            :  value of chord at s = blroot
C     rootpi            :  value of twist at s = blroot
C     nelem       :  number of (equidistant) elements in
C                     which blade will be divided, max nelmax
C     dels        :  length of s interval, rtot/number of elem
c     iaero       :  integer, giving index of first element
c                 partaking in aerodynamic calculations
C     prof(nelmax)      : profile identification for element i
C
C  *********************************************************************
C
      REAL    s,chord,twist,thckns,blroot,rootch,rootpi,dels

      INTEGER prof,iaero,nelem

      COMMON /elem/ s(0:nelmax),chord(0:nelmax),
     &              twist(0:nelmax),thckns(0:nelmax),prof(nelmax),
     &              blroot,rootch,rootpi,dels,iaero,nelem
C
C  *********************************************************************
C
C           dfax(k)  = d(f-axiaal)/ds /(.5*rho*vw**2)
C           dftan(k) = d(f-tangential)/ds /(.5*rho*vw**2)
C           dtorq(k) = d(axial torque)/ds /(.5*rho*vw**2)
C
C           notice that k = iaero - 1 is at blade root
C
C  *********************************************************************
C
      REAL    aprime,dfax,dftan,dtorq,dflmor

      COMMON/aerele/ aprime(0:nelmax),dfax(0:nelmax),
     &               dftan(0:nelmax),dtorq(0:nelmax),dflmor(0:nelmax)
```

INCLUDE elesys.i

```
C
CM    cost price data of the electrical system, including
CM    generators for Engcost
C
CM    a     generator cost coef.                [fl/kW^2]
CM    b     generator cost coef.                [fl/kW]
CM    c     generator cost coef.                [fl]
CM    c_c_1 cost price coef.                    [fl/kW]
CM    c_c_2 variable speed cost price coef.     [fl]
CM    ngen  number of generators                [-]
C
      REAL    a,b,c,c_c_1,c_c_2
      INTEGER ngen

      COMMON/elecsy/a,b,c,c_c_1,c_c_2,ngen
```

INCLUDE engcost.i

```
C
CM      Include file for engineering cost functions, values are
CM    set in user interface tab cost
C
CM      contains integer parameters which can have the value
CM      0 (zero) or 1 (one) to indicate wheter the cost of the
CM      concerned component should be included in the total cost.
C
CM      engbla    rotor blade cost
CM      enghub    hub cost
CM      engdrt    drive train cost
CM      engwfa    windfarm cost
CM      engels    electrical system cost
CM      engsfs    safety and control system cost
CM      engyam    yaw mechanisme cost
CM      engnac    nacelle cost
CM      engtow    tower cost
CM      engass    assembly cost

C
      INTEGER engbla,enghub,engdrt,engwfa,engels
      INTEGER engsfs,engyam,engnac,engtow,engass

      COMMON  /engcost /engbla,enghub,engdrt,engwfa,engels,
     &                  engsfs,engyam,engnac,engtow,engass
```

INCLUDE engpri.i

```
C
CM      Include file for engineering cost model component prices.
C

      REAL   priass,priwin,prisac,prihub,pridrt,
     &       priels,prinac,priyme,pritow,pribld

      COMMON /engpri/ priass,priwin,prisac,prihub,pridrt,
     &                priels, prinac,priyme,pritow,pribld
```

INCLUDE extloa.i

```
C
CM    Extreme loads on rotor blades at nodes between elements
C
CM    myext(i)    maximum flatwise moment             [Nm]
CM    mxext(i)    maximum edgewise moment             [Nm]
CM    fu_ext            cycle fatigue equiv. tower axial force    [N]
C
      REAL myext(0:nelmax),mxext(0:nelmax),fu_ext

      COMMON /extreme/ myext,mxext,fu_ext
```

INCLUDE fatigue.i

```
C
CM    1-P aero and mass fatigue loads on rotor blade at nodes
CM    between elements
CM    1-P fatigue equivalent moment on tower top.
C
CM    myfat(i)    1 P fatigue equiv. flatwise moment  [Nm]
CM    mxfat(i)    1 P fatigue equiv. edgewise moment  [Nm]
CM    mx(i)       1 P mass moment in edgewise direction     [Nm]
CM    fu_fat            1 P fatigue equiv. tower axial force[N]
C
      REAL myfat(0:nelmax),mxfat(0:nelmax),fu_fat
      REAL mx(0:nelmax)

      COMMON /fatigue/ myfat,mxfat,fu_fat,mx
```

INCLUDE fatmat.i

```
C
CM    Fatigue material constants for blade and tower material
CM    read from define.def
C
CM    mspar       -1/m is slope of S-N curve blade spar     [-]
CM    msteel            -1/m is slope of S-N curve tower mat.     [-]
C
      REAL  mspar,msteel

      COMMON /fatmat/ mspar,msteel
```

INCLUDE forcoe.i

```
C
CM    Blade node forces as function of the wind speed
CM    Rotor power as function of wind speed
CM    Rotor coefficients as function of wind speed
C
CM    axialf(k,i) array with axial force for wind speed interval
CM                i at element boundary k
CM    leadf(k,i)  array with lead force for wind speed interval
CM                i at element boundary k
CM    mflap(k,i)  array with flap moment for  wind speed interval
CM                i at element boundary k
CM    mlead(k,i)  array with lead moment for wind speed interval
CM                i at element boundary k
CM    nvwmax            maximum number of windspeed intervals.
CM    wpow(i)           aerodynamic power at wind speed i
C
      REAL     axialf(0:nelmax,nvwmax),leadf(0:nelmax,nvwmax),
     &         mflap(0:nelmax,nvwmax),mlead(0:nelmax,nvwmax),pitset

      COMMON /forces/ axialf,leadf,mflap,mlead,pitset
C
CM    wvwind(i)   wind speed i
CM    pitcon(i)   pitch angle at windspeed i
CM    rotspe(i)   rotor speed at windspeed i
C
CM      nvwind number of wind speed intervals
CM    deltav      wind speed increment in calculations
C
      REAL     wvwind(0:nvwmax),pitcon(nvwmax),rotspe(nvwmax),
     &         wpow(nvwmax),deltav
      INTEGER  nvwind

      COMMON /pvcurv/ wvwind,pitcon,rotspe,wpow,nvwind,deltav
C
CM    cp    aerodynamic power coefficient            [-]
CM    cq    torque coefficient                       [-]
CM    cdax  axial force coefficient                  [-]
CM    lamda tipspeed ratio                           [-]
CM    wpow  electrical power                   [-]
C
      REAL      cp(nvwmax),cq(nvwmax),cdax(nvwmax),lamda(nvwmax)

      COMMON /coef / cp,cq,cdax,lamda
```

INCLUDE genrator.i

```
C
CM    Generator data for the wind turbine control
C
CM    prated      rated electrical power
CM    closs constant loss of energy, ratio of prated
CM    vloss variable loss of energy, ratio of aerodynamic power
CM    lrated      logical true when rated power is
C
      REAL     prated,closs,vloss
      LOGICAL  lrated

      COMMON /generator/ prated,closs,vloss,lrated
```

INCLUDE geomet.i

```
C
CM    geometric wind turbine data for rotor blades and profile data
C
C  ********************************************************************
C
C     nprmax            : maximum number of aerofoils
C     nrmax       : maximum number of chord/twist changes in input
C     rchord(i)   : r values at which chordlength is defined
C                   in input file 'geodat.
C     chordi(i)   : chordlength at rchord( ), in 'geodat'
C     rtetap(i)   : r values at which twistangle tetati is
C                   defined in input file 'geodat'.
C     tetapi(i)   : values of twistangle teta-pitch at
C                   rtetap( ), defined in 'geodat'. this is
C                   the pitch angle for pitset (pitch setting)
C                   equal to zero.
C
C     sldty     :  solidity of the rotor
C       alfa(i,j)   : angle of attack array for aerodynamic coefficients
C                     for profj
C       clin(i,j)   : cl value at alfacl(i) defined in 'geodat' profj
C       cdin(i,j)   : cd value at alfacd( )
C       cmin(i,j)   : cm value at alfacm( )
C     dia         : rotor diameter
C     nob         : rotor number of blades
C       nchdat      : number of chord data pairs in
C                             input file (<20)
C       ntedat      : number of teta data pairs in
C                             input file (<20)
C       nthdat      : number of thickness data pairs in
C                             input file (<20)
C       nclcd(iprof): number of cl data pairs in input file
C                     (<mxaedt), for profile iprof
C       nuprof      : number of different profiles (max 15)
C       rp(iprof)   : radius where profile changes to (iprof + 1)
C     rtip      : radius tip device (if ltip .TRUE.)
C     tip_t     : thickness tip profile in %  tip chord
C     root_t          : thickness root profile in % root chord
C
C       sectio(15)  : character variable with names of aero sections
C
      INTEGER  nob,nchdat,ntedat,nthdat,nclcd,nuprof

      REAL     rchord,chordi,rtetap,tetapi,rthick,thicki,alfa,
     &         clin,cdin,cmin,dia,rp,root_t,tip_t,rtip,sldty

      CHARACTER*128  sectio

      COMMON /geom  / rchord(nrmax),chordi(nrmax),
     &                rtetap(nrmax),tetapi(nrmax),
     >                  rthick(nrmax),thicki(nrmax),
     >                alfa(mxaedt,nprmax),clin(mxaedt,nprmax),
     >                cdin(mxaedt,nprmax),cmin(mxaedt,nprmax),
     >                dia,nob,root_t,tip_t,rtip,sldty,
     >                nchdat,ntedat,nthdat,nclcd(nprmax),
     >                nuprof,rp(nprmax-1)
      COMMON /geopro/ sectio(nprmax)
```

INCLUDE hub.i

```
C
CM    engcost coefficients for the hub
C
CM    c_c_1 cost coefficient hub                [fl/dia**(1./2.7)]
CM    c_c_2 cost coefficient blade bearings           [fl/blade]
CM    c_c_3 cost coefficient hub                [-]
CM
      REAL    c_c_1,c_c_2,c_c_3

      COMMON/hb/c_c_1,c_c_2,c_c_3
```

INCLUDE nacelle.i

```
C
CM    cost price coefficient data of the nacelle for the Engcost
CM    model
C
CM    m_c_1   mass coef. of nacelle             [fl/m^3]
CM    c_c_1   cost price coef. of nacelle       [fl/kg]
C

      REAL  m_c_1,c_c_1

      COMMON/nacell/m_c_1,c_c_1
```

INCLUDE paramet.i

```
C
CM    Definitions of parametric variables. Do not change without
CM    recompilation of the total program.
C
CM    nelmax      maximum number of blade elements
C
      INTEGER    nelmax
      PARAMETER (nelmax=40)
C
CM    nvwmax      maximum number of wind speed intervals
C
      INTEGER    nvwmax
      PARAMETER (nvwmax=128)
C
CM    nprmax      maximum number of profiles
C
      INTEGER    nprmax
      PARAMETER (nprmax=16)
C
CM    nrmax maximum number of chord/twist changes in input
C
      INTEGER    nrmax
      PARAMETER (nrmax=16)
C
CM    maxcon      maximum number of conditions for noise calculations
C
      INTEGER    maxcon
      PARAMETER (maxcon=1)
C
CM    maxcon      maximum number of coefficient (cl,cd,cm) per profile
C
      INTEGER    mxaedt
      PARAMETER (mxaedt=192)
C
CM    dimmax      maximum number of design parameters to be optimized
C
      INTEGER    dimmax
      PARAMETER (dimmax=10)
C
CM    parameters for the approximation and evaluation of
CM    approximation routines.
C
CM    nptsmax     maximum number of points used in the function
CM          approximation
C
      INTEGER      nptsmax
      PARAMETER   (nptsmax = 256)
C
CM    neptma      maximum number of data points to evaluate fit with 256
C
      INTEGER          neptma
      PARAMETER       (neptma=1)
C
CM    edwkln      dimension of arrays FITIWK,FITVLS,RESIDS
C
      INTEGER          edwkln
PARAMETER       (edwkln = 1001)
```

INCLUDE parcost.i

```
C
CM    Include file for parametric cost functions.
C
CM    contains integer parameters which can have the value
CM    0 (zero) or 1 (one) to indicate wheter the cost of the
CM    concerned component should be included in the total cost.
C
CM    parrot      rotor cost
CM    pargea      gearbox cost
CM    parsyg      synchronos generator cost
CM    parasy      asynchronos generator cost
CM    parddg      direct drive generator cost
CM    parpel      power electronics cost
CM    partra      transformer cost
CM    parnac      nacelle and bedplate cost
CM    parhyd      hydraulics cost
CM    parcos      control system cost
CM    parprs      primary shaft cost
CM    parbps      bearing of primary shaft cost
CM    paryab      yaw bearing cost
CM    parfsb      full size brake cost
CM    parpab      parking brake cost
CM    parass      assembly cost
CM    parwif      wind farm cost
CM    partow      tower cost
C
      INTEGER parrot,pargea,parsyg,parasy,parddg,parpel,partra
      INTEGER parnac,parhyd,parcos,parprs,parbps,paryab
      INTEGER parfsb,parpab,parass,partow,parwif

      COMMON  /parcost / parrot,pargea,parsyg,parasy,parddg,parpel,
     &                   partra,parnac,parhyd,parcos,parprs,
     &                   parbps,paryab,parfsb,parpab,partow,parass,
     &                   parwif
```

INCLUDE parpri.i

```
C
CM    Include file for parametric component prices.
C
CM Costs output variables:
C
      REAL crotor
      REAL cgear
      REAL cstdgen
      REAL cdirdrivegen
      REAL cpowel
      REAL ctrans
      REAL cbedplate
      REAL chydr
      REAL ccontrol
      REAL cvent
      REAL cshaft
      REAL cshaftbear
      REAL cyawbear
      REAL cfullbrake
      REAL cparkbrake
      REAL ctower
      REAL cmisc

      REAL cfound
      REAL cland
      REAL csite
      REAL ctran
      REAL cerect
      REAL cconnect
      REAL cremote
      REAL cgeneral
      REAL ceng

      COMMON/parpri/ crotor,cgear,cstdgen,cdirdrivegen,cpowel,
     &               ctrans,cbedplate,chydr,ccontrol,cvent,cshaft,
     &               cshaftbear,cyawbear,cfullbrake,cparkbrake,
     &               ctower,cmisc,
     &               cfound,cland,csite,ctran,cerect,cconnect,
     &               cremote,cgeneral,ceng
```

INCLUDE safcon.i

```
C
CM    cost price data safety and control system for Engcost
C
CM    c_c_1   base price of control and safety  [fl]
CM    c_c_2   cost price coef. of actuator            [fl/kW]
CM    c_c_3   cost price coef. of pitching            [fl]
CM      sf_1      service factor of actuator          [-]
CM      sf_2      service factor of blade             [-]
C
      REAL    c_c_1,c_c_2,c_c_3,sf_1,sf_2

      COMMON/safcnt/c_c_1,c_c_2,c_c_3,sf_1,sf_2
```

INCLUDE spect.i

```
C
CM    data for the load prediction module
C
CM    uaver array met 10 minuten gemiddelde windsnelheden
CM    aa0pa array met vlaag amplituden
CM    wisa  array met aantal wisselingen per levensduur
CM    pmoda array met mode nummer
CM    imxgus      aantal gedefinieerde vlagen
CM    rotations number of rotor rotation per life time
CM    vstorm      extreme wind speed according to IEC wind turbine class
C
CM    lf    array with flatwise load cycles format
CM          igus,ielem,(1=range,2=mean) level
CM    lf    array with edgewise load cycles format
CM          igus,ielem,(1=range,2=mean) level
C
      REAL    uaver,aa0pa,wisa,vstorm
      REAL    lf,le
      INTEGER imxgus,pmoda
      REAL*8  rotations

      COMMON /gusts / uaver(100),aa0pa(100),wisa(100),pmoda(100),
     &                imxgus,vstorm,rotations,
     &                lf(100,0:nelmax-1,2),le(100,0:nelmax-1,2)
```

INCLUDE storm.i

```
C
CM    Data of blade loads at extreme windspeed
C
CM    mysto(k)    vector with flat moment at element boundary k   [Nm]
CM    mxsto(k)    vector with edge moment at element boundary k   [Nm]
CM    mzrst       rotor torque at extreme windspeed        [Nm]
CM    fu_sto            axial force during storm on tower head          [N]
CM    stotor            rotor torque during storm                [Nm]
C
      REAL mysto(0:nelmax), mxsto(0:nelmax),fu_sto,torsto

      COMMON /storm/ mysto,mxsto,fu_sto,torsto
```

INCLUDE tower.i

```
C
CM    cost price data of the tower for the Engcost module
C
CM    c_c_1 mass cost coef. tower               [fl/kg]
CM    c_d_tt      tower top diameter coefficient            [-]
CM    c_buck      buckling constant
CM    esteel      elasticity modules tower materialtower material[N/m^2]
CM    smste density of tower material           [kg/m^3]
CM    mstrex      maximum allowable static stress           [N/m^2]
CM    mstrfa      maximum allowable fatigue stress    [N/m^2]
CM      mstryi  yield stress                          [N/m^2]
CM    msteel      -1/m is slope of S-N curve          [-]
CM      a   tower eigenfreq. distance from rpmmin
CM      b       tower eigenfreq. distance from rpmmax
CM      c   tower eigenfreq. distance from nob * rmpmin
CM      d   tower eigenfreq. distance from nob * rmpmax
C
      REAL  c_c_1,c_d_tt,c_buck,esteel,smste,mstrex,mstrfa,mstryi
      REAL  a,b,c,d

      COMMON/twr/c_c_1,c_d_tt,c_buck,esteel,smste,mstrex,mstrfa,mstryi,
     &          a,b,c,d
```

INCLUDE towprop.i

```
C
CM    tower design data of the Engcost module
C
CM    dia_tt      diameter tower top                  [m]
CM      dia_tf    diameter tower foot                 [m]
CM    t_tf  chosen thickness of tower foot wall [m]
CM    t_tt  tower top wall thickness            [m]
CM    t_towf      the tower foot wall thickness
CM    massto      tower mass                        [kg]
CM    mastop  mass on tower top                     [kg]
CM    futow
C
      REAL  dia_tt,t_tt,dia_tf,t_towf,massto,mastop,futow

      COMMON/towprp/dia_tt,t_tt,dia_tf,t_towf,massto,mastop,futow
```

INCLUDE wepp.i

```
C
CM    COMMON FOR THE ENERGY YIELD WEIBULL DISTRIBUTIONS
CM
CM    pkl   vector(1:nvwmax) with the hr’s per wind interval
CM    wk    wk10 (weybull k factor at 10 m, for (2))
CM    vhavv Average windspeed at hubheight
CM    wk10  weybull k factor at 10 m
CM    v10   average windspeed at 10 m heigth
CM    hhub  hub heigth
CM    z0    terrain roughness parameter for to determine
CM          wind speed at hub heigth
CM    vctui cut in  wind speed
CM    vcuto cut out wind speed
CM    vrated      rated wind speed
CM    rhoair      density of air
C
      REAL     pkl(nvwmax)
      REAL     wk10,v10,hhub,z0,vcuti,vcuto,vrated,rhoair
      INTEGER  ivci, ivr,ivco

      COMMON /weppco/ pkl,wk10,v10,hhub,z0,vcuti,vcuto,
     &                vrated,rhoair,ivci,ivr,ivco
```

INCLUDE winfar.i

```
C
CM    cost coefficient data windfarm cost for the Engcost module
C
CM    c_c_1   cost price coef. connection auxiliaries [fl/kW]
CM    c_c_2   cost price coef. of infrastructures     [fl/m]
CM    c_c_3   fees                              [fl]
C
      REAL c_c_1,c_c_2,c_c_3

      COMMON/winfr/c_c_1,c_c_2,c_c_3
```

INCLUDE yawmec.i

```
C
CM    cost price coefficient of the yaw mechanism for the
CM    Engcost module
C
CM    c_c_1   cost price coef. of yaw mechanism [fl/kg]
C
      REAL  c_c_1

      COMMON/yawmch/c_c_1
```

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Abstract

This report contains the theory and user manual for the computer tool BLADOPT. BLADOPT is a numerical optimization tool for designing horizontal axis wind turbine rotor blades.
The objective function of the optimization is the cost of energy calculated according to the recommended procedures of the IEA. This implies that not only the energy yield but also the cost of the complete wind energy system has to be determined. The rotor performance i.e. power curve and design loads are predicted using a quasi-static rotor code and load module taking the chosen power control mode into account. Two different component cost modules are implemented, a parameteric one using only geometric parameters of the wind turbine and design wind spectrum parameters and a model based on engineering models for the tower and the rotor blade making use of a load prediction model.

The report describes the general set up of the optimization tool and each individual module. The installation procedure for Windows 95/98 and WindowsNT and the deinstallation procedure.

The user's manual describes the entire user interface screens and each button and text box of those screens.

To be able to understand the source code of the component cost modules the include files and common block parameters are described in the Annex.

Keywords Windturbine optimization, Theory and User manual

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