Design Synthesis Exercise

Baseline Report

DWT

Design of the Delft University of Technology Wind Turbine

Group N3

May 1, 2007

Faculty of Aerospace Engineering

Delft University of Technology

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Design Synthesis Exercise

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SE Content

Table 1: SE Content

Product	PP	BR	MR	FR
DSE work flow diagrams	-	-	-	-
DSE work break-down structure	-	-	-	-
DSE project approach description	-	-	-	-
DSE Gantt chart	-	-	-	-
DSE team organization/organogram and HR allocation	-	-	-	-
Functional flow diagram(s)	-	5	-	-
Functional breakdown	-	7	-	-
Requirements discovery tree and requirements structuring	-	9	-	-
Technical resource budgets (allocation and contingencies)	-	29	-	-
Technical risk assessment and risk map	-	39	-	-
Design option structuring (tree)	-	19	-	-
Market Analysis	-	-	-	-
Interface identification / N2 charts	-	-	-	-
Trade method, rationale and organization	-	-	-	-
Trade criteria	-	-	-	-
Criteria weight factors	-	-	-	-
Trade summary table	-	-	-	-
Operations and logistic concept description	-	-	-	-
Project design and development work flow diagrams	-	-	-	-
Project Gantt chart	-	-	-	-
Cost break-down structure and cost estimate	-	-	-	-
H/W, S/W block diagrams (interactions, flows)	-	-	-	-
Compliance Matrix	-	-	-	-

Version Documentation

Table 2: Version Documentation, part 1

	Name Document	Author	Vers.	Checked by	Ap.	Date
1	FFD	Gide, Jasper	1.0	Dirk, David	NO	24-04-07
	FFD	Gide, Jasper	2.0	Gide	NO	25-04-07
	FFD	Gide	3.0	Team	NO	26-04-07
	FFD	Gide	3.1	Mario	YES	26-04-07
	FFD text	Gide	1.0	Team	NO	25-04-07
	FFD text	Gide	1.1	Mario	YES	25-04-07
2	FBS	Steven, Mario	1.0	Team	NO	24-04-07
	FBS	Gide	2.0	Mario	YES	26-04-07
	FBS text	Steven	1.0	Dirk	NO	25-04-07
	FBS text	Steven	1.1	David	YES	27-04-07
3	RDT	Dirk, Dinand	1.0	Mario, Gide	NO	24-04-07
	RDT	Dirk, Dinand	1.1	Mario	NO	25-04-07
	RDT	Dirk, Dinand	2.0	Team	NO	25-04-07
	RDT	Dirk, Dinand	2.1	Dirk, Dinand	NO	26-04-07
	RDT	Dirk, Dinand	2.2	Mario	NO	27-04-07
	RDT	Dirk, Dinand	2.3	Mario	YES	27-04-07
	RDT text	Dinand, Dirk	1.0	Mario	NO	25-04-07
	RDT text	Dinand, Dirk	1.1	Dirk	NO	26-04-07
	RDT text	Dirk, Steven	1.2	Mario	NO	27-04-07
	RDT text	Dirk, Steven	1.3	Mario	YES	27-04-07
4	Sustainable development	Reinder	1.0	Mario	NO	24-04-07
	Sustainable development	Reinder	2.0	David	YES	27-05-07
5	Budget Breakdown	Evgeni	1.0	Jasper	NO	24-04-07
	Budget Breakdown	Evgeni	2.0	Reinder, Steven	NO	25-04-07
	Budget Breakdown	Evgeni	2.1	Mario	NO	25-04-07
	Budget Breakdown	Evgeni	2.2	Mario	YES	26-04-07

Table 3: Version Documentation, part 2

	Name Document	Author	Vers.	Checked by	Ap.	Date
6	Resource Allocation	Jasper, Steven	1.0	Team	NO	25-04-07
	Resource Allocation	Jasper, Steven	1.1	Mario	YES	27-04-07
7	Project Costs	Reinder, Evgeni	2.3	Team	NO	25-04-07
	Project Costs	Reinder	3.0	Team	NO	27-04-07
	Project Costs	Reinder	3.1	David, Mario	YES	27-04-07
8	DOT introductory text	Mario	1.0	Team	YES	25-04-07
	DOT tower	Steven, Mario	1.0	Mario	NO	25-04-07
	DOT tower	Steven	1.1	Mario	YES	26-04-07
	DOT tower text	Steven	1.0	Mario	YES	26-04-07
	DOT Nacelle	Gide	1.0	Mario	YES	26-04-07
	DOT Nacelle text	Gide	1.0	Mario	YES	27-04-07
	DOT Control	Dinand	1.0	Dirk	NO	26-04-07
	DOT Control	Dirk	1.1	Mario	NO	27-04-07
	DOT Control	Dirk, Dinand	1.2	David, Mario	YES	27-04-07
	DOT Control text	Dinand	1.0	Dirk	NO	26-04-07
	DOT Control text	Dinand	1.1	Mario	YES	27-04-07
	DOT rotor	Dinand, Evgeni	1.0	Team	NO	26-04-07
	DOT rotor		1.1	Mario	YES	27-04-07
	DOT rotor text	Dinand Evgeni	1.1	Mario	YES	27-04-07
	DOT foundation	Jasper	1.0	Mario	NO	26-04-07
	DOT foundation	Jasper	1.1	Mario	YES	27-04-07
	DOT foundation text	Jasper	1.0	mario	NO	26-04-07
	DOT foundation text	Jasper	1.2	Mario	YES	27-04-07
9	Risk Assessment	David	1.0	Team	NO	26-04-07
	Risk Assessment	David	1.1	Team	NO	26-04-07
	Risk Assessment	David	1.2	Mario	YES	27-04-07
10	SE content	Dirk	1.0	Mario	YES	27-04-07
11	Summary	Dinand	1.0	Mario	NO	27-04-07
	Summary	Dinand	1.1	Mario	YES	27-04-07
12	ListOfSymbols	Dirk	1.0	Steven, Dirk	YES	27-04-07
13	Information acquisition	Team	1.0	Evgeni, Mario	YES	27-04-07
14	Preface	Jasper	1.0	Mario	NO	27-04-07
	Preface	Jasper	1.1	Mario	YES	27-04-07
15	Project Approach	Steven	2.0	Evgeni, Mario	YES	27-04-07
16	Energy Estimation	Gide	1.0	David	NO	26-04-07
	Energy Estimation	Steven	1.1	David, Mario	YES	27-04-07
17	Introduction	Gide	1.0	David	NO	27-04-07
	Introduction	Gide	1.1	David, Mario	YES	27-04-07
18	Baseline report	Reinder	1.0	Mario	NO	27-04-07
	Baseline report	Reinder	1.1	Team	NO	1-05-07
	Baseline report	Reinder	1.2	Mario	YES	1-05-07

Preface

This baseline report is written for the Design Synthesis Exercise (DSE) with the purpose of showing the work progress and findings after completing the organisational and planning phases. It also deals with the orderly documentation methods used while gathering information.

This document consists of several parts and therefor it is not always necessary to read the whole report. In chapter 3 till 10 the project is inspected entirely using technical system engineering techniques. It is recommendable to read these chapters chronologically to get a clear view of how the future stages of the project should be. Chapter 11 and 12 are chapters that are written to increase the knowledge of specific areas of the wind turbine and thus can all be read separately.

At the moment several members have been greatly helpful to produce this paper. First of all our tutor and assistants in the wind energy sector who lead us in the right direction, secondly our system engineering instructor and finally everyone who we have interviewed so far. These interviews were the basis for a better understanding of the possibilities in designing an innovative wind turbine.

List of Symbols

Table 4: Acronyms

Notation	Explanation	Dimension
C_p	Pressure Coefficient	$[-]$
C_t	Costs in year t	$[euro]$
S_t	Revenue in year t	$[euro]$
r	Real interest rate	[%]
T	Wind turbine lifetime	$[year]$
NPV	Net Present Value	$[euro]$
V	Value of the wind turbine	$[euro]$
HR	Human recourse	$[-]$
C_l	Lift coefficient	$[-]$
C_d	Drag coefficient	$[-]$

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Summary

As part of the Design Synthesis Exercise 2007, an innovative horizontal axis wind turbine in downwind configuration has to be designed. In this report all preparations that are made to give guidance and structure in the upcoming design phase are described.

The Project Objective Statement is formulated as follows:

To design, with nine students in ten weeks, an innovative, down-wind configuration wind turbine incorporating TU Delft technologies, to form a basis for a TU Delft design in an inter-academia design competition.

In the period before starting the actual design process, guidelines for the designers are deducted from the main objectives. The main objectives of this project are:

- The design should be innovative, incorporating TU Delft technologies to damp out the loads due to unsteady flows.
- The turbine should provide a platform for research into a wide range of subjects related to wind turbines.
- The turbine should be a 500 kW machine, however it should be possible to upscale the system.
- The rotor should be placed in downwind configuration.

From these objectives, a requirement flow down is conducted to discover all requirements the design has to fulfil. From that, initial design option trees for all subsystems are constructed.
On all requirements a risk assessment is done to identify the parameters that pose threat to the overall success of the project. It was found that the highest risk comes from the innovative character of the design. Identifying, understanding, and incorporating new technologies that are often still in development has potential to seriously harm the project.
To actually provide the structure during design, the workload is broken down in a work breakdown structure and a Gantt chart. The design process is depicted in a work flow diagram to clarify the temporal division of workload.

Chapter 1

Introduction

At present more and more people around the world are becoming aware of the environmental effects of their current lifestyles. Specially the energy consumption is growing larger and larger every year and given that the world's primary energy resource consists of fossil fuels, it doesn't take a rocket scientist to figure out that the carbon dioxide emissions will continue increasing dramatically. But there is a bright spot on the lining; renewable energy resources are gaining ground on fossil fuels and specially wind energy is emerging as a viable alternative for the future energy needs.

The trends in the wind energy business are larger turbines and cheaper energy production and because of that, new innovative designs are needed. Our goal is to design a downwind wind turbine and tackle the difficulties, such as unsteady flows due to the tower wake, incorporating TU Delft technologies. The design has to prepare ground for a 2008 competition in wind turbine design and has to serve as a research platform for innovative designs.

In this baseline report the first part of the design is explained. In chapter 2 the project approach is described. In chapter **??** a functional analysis is done to get a better understanding of all the functions of an innovative wind turbine afterwards the requirements are analysed in chapter 5. With the knowledge from chapter 3, chapter 4, chapter 5 and the information from the interviews with the TU Delft staff in chapter 6 a preliminary design option tree in chapter 7 is established. Commencing with chapter 8 a new stage of the report begins. In chapter 8 the research allocation is described followed by the project costs in chapter 9. In chapter 10 the risk assessment is established and in chapter 11 the annual energy yield of the wind turbine is estimated. The last chapter, chapter 12 describes our sustainable development strategy.

Chapter 2

Project Approach

2-1 Challenges

The Project Objective Statement is formulated as follows:

To design, with nine students in ten weeks, an innovative, downwind configuration wind turbine incorporating TU Delft technologies, to form a basis for a TU Delft design in an inter-academia design competition.

In coming to a satisfactory result the team is faced with several challenges:

- Defining what is innovative
- Finding TU Delft Technology
- Finding other innovative concepts
- Incorporating a downwind configuration
- Finding a solution for unsteady loads

These challenges are approached as follows:

Defining what is innovative

To define what is innovative one first needs to know what is conventional. After that you can define what is innovative by looking if a particular concept can add an improvement to the conventional concept.

Finding TU Delft Technology

At the TU Delft there is a large wind energy department: DUWIND. The people working at this department should be visited to gain insight into innovative wind turbine options.

Those people know also other TU Delft departments and people of interest which they can recommend to interview.

Finding other innovative concepts

To find other innovative concepts one can search in the literature on wind energy. Many design concepts are made in the past, which never came into production, or only as a prototype. Also the own knowledge and technical insight should be used in this part.

Finding a solution for unsteady loads

To solve this issue the team has to look for solutions incorporating smart rotor technology and its control.

2-2 Further development

This research should lead to different design concepts. As only one concept is needed, it is necessary to do a trade-off between the various concepts. This trade-off is first done with the killer requirements and needs to be iterated (with other criteria) until one concept is selected. This is the pre-design.

At this point it is useful to map the interfaces, and the following design features should be known:

- Blade configuration
- Smart rotor concept
- Power controller type
- Generator type
- Tower structure type
- Foundation type

When taking these interfaces in mind the design can be further developed and at the end the final performance can be tested.

Chapter 3

Functional Flow Diagram

3-1 The function of the functional flow diagram

The functional flow diagram (FFD) is a powerful tool for functional analysis. It is a step by step diagram of the system's functional flow. The goal of the FFD is to obtain a better understanding for the functions of the system, in this case a wind turbine, and their sequence. First the layout of this diagram is explained, followed by a more detailed explanation of the functions.

3-2 Layout of the FFD

The FFD that is shown in Appendix A has several levels for more detailed functional analysis. The top level describes the total function of the wind turbine. The functions in this level have a grey background color and are numbered with integers and zero decimals. The second digit indicates a second level, the third digit a third level and so on. Every level explains the flow more in depth but it will also cause more confusion due to a lot of functions. In the circles the "and" and "or" gates are indicated and the encircled '1' refers to the next page. where the specific part of the flow is shown more in depth. The second level is arranged vertically to make the FFD well organised.

3-3 Function explanation

The top level of the FFD is already explained in the last paragraph, The flow goes from production to decommission. To start up, the condition of the wind has to be known. Afterwards the blades (blade pitch angle and if possible the blade geometry) have to be adapted to the current wind speed and the yaw angle has to be adapted to the wind direction. The largest part in this FFD is the operation of the wind turbine. The wind turbine has to convert energy and can be used for research purposes. To convert the wind energy efficiently there are several parameters that have to be monitored. These parameters will be used to set the blades to idle if necessary. This will be the case when the wind speed is larger than the cut-out wind speed. Beside this monitoring system there is a system that will detect failures and respond by turning the blades to set the rotor to idle and brake if needed.

Chapter 4

Functional Breakdown Structure

A functional breakdown structure is a logical grouping of functions. The breakdown is presented in the form of an AND tree. There is no time information contained in the tree. The functional breakdown of the wind turbine is presented in figure B.

The tree splits the main function, in this case *Generate power and Being a Research platform*, into different sub-functions, which are also split up into sub-sub-functions, which all have to be incorporated in the design to comply with the main function.

Chapter 5

Requirements Discovery Tree

5-1 Requirements analysis

The requirement analysis process is executed in three steps:

1. Formulate the mission need statement
2. Discover the system requirements
3. Flow down the subsystem requirements

When conducting the three steps, the functional analysis should always be considered as a reference. This is of great assistance to the process.

5-1-1 Formulate the mission need statement

To design with nine students in ten weeks, an innovative, down wind configuration wind turbine incorporating TU Delft technologies, to form a basis for a TU Delft design in an inter-academia design competition.

5-1-2 Discover the system requirements

Most constraints are dictated by the customer's wishes, these are:

- The team should design a 500 kW wind turbine.
- The turbine should be designed incorporating TU Delft technologies.
- The design team should come up with a single rotor design, placing the rotor in down wind configuration.
- The design should incorporate innovative solutions that;

  - Decrease the effect of unsteady loads
  - Decrease the total cost of the turbine
  - Decrease the amount of required maintenance (once per two years)
- The possibility of up scaling should be taken into account in the design.
- The entire wind energy conversion system should be designed to perform as a research tool.
- The maximum price per kWh is set at €ct6.5.
- The system should not produce unacceptable noise levels (about 100 dB is acceptable).
- The system should be visually attractive.
- The design work should be done by nine members and be finished for its due date on 22-06-2007.

Based on these constraints the following system requirements are defined:

- Be able to control and monitor the system
- The wind power needs to be converted into electricity
- The structure has to withstand all kind of loads

5-1-3 Subsystem requirements flow down

When the system requirements are defined, the subsystem requirements can also be described. This is done by several brainstorming sessions in order to be sure nothing has been overlooked or done twice. In the constraints-branch of the tree, it is useful to come up with hard numbers to accompany the constraints as much as possible. This makes testing for constraints easier. These values are usually dictated by the customer's wishes. In the other branch, the general requirements stated above should be 'broken down' into more specific requirements for different subsystems.

5-2 Requirement discovery tree

In order to clarify the (sub)system requirements, a requirement discovery tree is essential. Such a tree helps to give a general overview of the requirements imposed on the design by means of the customer's wishes and demands. The requirement discovery tree applicable for this design project can be seen in C-1 and C-2

5-2-1 Legend of the requirement discovery tree

- The mission is visualised by the larger rounded rectangle

- The dichotomy is visualised by the smaller rounded rectangles
- Systems requirements are visualised by the larger squares
- Subsystem requirements are visualised by the smaller squares, some of the subsystems are further extended with some additional requirements
- The off-page reference is visualised with a circle

5-2-2 Requirement specification

In order to identify the most important requirements, a classification into the most important requirements has been made. This will speed up the trade-off of the design option tree to eliminate certain strawman design concepts. The classification is as follow:

Killer requirements

These are the requirements which drive the design to an unacceptable extent. [Hamann, 2006]

1. Innovative design - The design should incorporate innovative features
2. Downwind configuration - The wind turbine should incorporate a downwind configuration
3. Incorporating TU Delft Technology - Making use of TU Delft Technologies
4. Research platform - There should be room for research on the wind turbine
5. Costs - The maximum price per kWh should not be exceeded
6. Power production - The turbine should provide electricity
7. Time - The project should be finished before the end of the design synthesis exercise

Driving requirement

These are the requirements which are user defined or derived, and drive the design more than average. [Hamann, 2006]

1. Low maintenance - There should be little maintenance operations
2. Smart control - The rotor should use smart rotor technologies
3. Sustainability - The wind turbine should be sustainable over its life span.

Chapter 6

Information Acquisition

6-1 Approach

For the entire project, the information acquisition is a very important stage. Many issues have to be researched properly in order to be able to understand all different innovative aspects and their implications. As a first step, several specialists within the TU Delft are interviewed in order to pinpoint relevant innovative research areas and gain some insight in their research fields. Books, papers and references are collected simultaneously.

6-2 Interviews

6-2-1 Ir. J.J.E. Teuwen, AE Production Technology

At the TU Delft, major efforts are made in developing fiber-reinforced thermoplastic materials for manufacturing wind turbine blades. At the moment, the research is a state-of-the-art topic; patents are pending and probably very few other people in the world have a comparable knowledge about the subject.

The main advantage seems to be the complete ability to recycle the material and the ease of manufacturing due to the very low viscosity of the matrix material (the same as plain water). The matrix material completely resolves leaving the fibres behind. It will be hard to reuse the remaining fibres as uncut mats, but when the fibres are chopped, reuse is perfectly possible, for instance, in non-critical load bearing parts.

Ms. Teuwen pointed out that at the moment, research has been focusing on bending and tensile strengths. Compression and fatigue tests are on the way. An other problem where the research is focussing on is the adhesive quality between the matrix and the fibres. Because of the above mentioned problem, fatigue tests will be disappointing. A 2 or 3 year term is assumed to resolve this issue. Researchers are working in close collaboration with some selected industry partners to come up with an answer.

6-2-2 Ir. B.A.H. Marrant and Ir. A. Barlas, AE Wind Energy

Smart rotor control can be used to reduce the unsteady loads on the rotor due to the constantly changing wind field. In doing so, fatigue is reduced significantly and the total rotor weight can be lowered. The basic idea is that the control surfaces on the blades change the aerodynamic properties such that the unsteady loads are filtered out. Because of the unsteady, unknown flow field and the fast rotating rotor, these rotor control devices should react very fast. By adding complexity to the blades, the need for maintenance increases, so this should be carefully monitored.
There are basically two approaches to tackle this problem: knowing the flow field and adapt the control surfaces accordingly (active control) or measure the deformation of the blade, deduce the wind force and react with the control surfaces.
Predicting the flow field ahead is quite challenging. This can for instance be achieved with a Doppler anemometry, but is quite expensive and possibly does not provide sufficient data quality. When measuring the deformations of the blade with strain gauges at the root and accelerometers at the tip, a much cheaper solution is presented with known and accurate measuring techniques. Attention must be payed to the total system response time (measurement, controller, control device). When the system does not react very fast, the actual control device can be much less effective, or even worse, the load correction could be in phase with the unsteady load. A very well designed controller is an implicit step-stone towards the realisation of this concept.

There are several options with respect to the control device:

1. Trailing edge flaps, which can be made of piezoelectric (PZE) materials.
2. MEM: Small Micro Eelectro-Mechanical tabs at the trailing edge which come out vertically. They result in a higher change in drag than is the case with flaps. Very high frequencies can be achieved (50-70 Hz). This ends up in a very simple system, but there is only a single on/off mode and its behavior is highly non-linear.
3. PZE fibres in the blade (for instance 45 deg incidence angle with respect to the span), which induces a twist in the blades.
4. Leading edge devices: Because the operation mode of the blades is at the maximal C_l/C_d, the stall angle of attack is quite close to the operation angle of attack. When wind gusts locally increase the angle of attack, the blade can stall. What happens when the control surface is deflected in the stalled area is unknown so far. However, recent experiments, performed by Barlas and others, show that perhaps this isn't a problem after all. Also leading edge devices can make the blade too complex.
5. Inflatable blade sections: Change camber locally or over the entire chord.

An other feature mentioned, are optical fibres. Although expensive, they can provide very relevant data about the blades structural state. System health monitoring and consequent maintenance actions can be planned efficiently.

Piezoelectric materials can also be used as measuring devices.

6-2-3 Ir. W.A Timmer, AE Wind Energy

The aerodynamics are an important subject in wind energy. The control, noise and performance of the turbine are strongly influenced by aerodynamics. There are some areas that need special attention.

Noise reduction

The major source of noise is the interaction of turbine parts with turbulence. This is the case at the blade tips and less important at the blade in the tower shadow. To reduce the noise at the blade tips two strategies can be used.

- Reduce the tip vortex: The tip vortex is generated because of the abrupt change in lift, this can be reduced with a decreasing camber, twist and cord to the end of the blade. Another option is the use of winglets.
- Reduce interaction between the blade tips and the vortex: When a straight edge is used at the tip, the vortex will collide with the tip and produce noise. An effective way to reduce this collision is to cut out the edge as can be seen in figure 6-1.

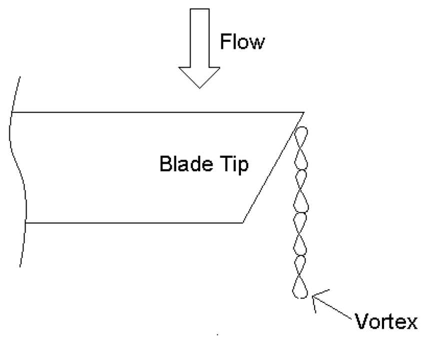

Figure 6-1: Edge cut-off of a blade tip

Performance

To improve the performance there are a few options;

- Blades directly connected to the hub (no cylindrical part at the blade root). There is a wind turbine produced by Enercon with this concept and it has a C_p of 0.52. This option is also very aesthetic.
- Flatback profiles have the advantage that they produce more lift and are thicker (thus better for the structure). The disadvantage is that the drag of a flatback profile is larger, but this can be reduced by using a hollow trailing edge.

Control

Some remarks about the control subsystem:

- Gurney flaps are bad for the performance.
- Monitoring is very important, the best option is monitoring in front of the blades. Implementing pressure holes are too difficult for an operational wind turbine.

6-2-4 Ir. M. Zaaijer, AE Wind Energy

Tower

Mr. Zaaijer has performed a design study for a 10 MW wind turbine, where he used a downwind configuration with a truss construction for the tower. He mentioned that there are several construction options for the tower. A design using a lattice configuration has more flow disturbances than a circular tower, but the disturbances are smaller, so overall there is a reduction in the effect of the flow over the blades. For this reason a conventional circular tower is probably not a good design option for a downwind configuration. Also a combination of these can be used for the tower. A truss at the lower part and a circular part at the upper part. This has been applied in the past. An innovative, but very expensive and experimental option would be to shape the tower like an airfoil, which will passively stabilise the whole tower in the right wind direction.

Rotor

To remove the moments acting on the hub, a *wigwag* system can be used. Here the blades are rigidly connected to each other and with a hinge to the hub. A disadvantage is when the rotor is turning at low speed; then the centrifugal forces are small and the deflections can become to large, allowing the blades to get too close to the tower. This system is normally only applied on a two blade rotor.
An other idea is that the blades are all separately hinged to the hub, also removing the moments. This has the same disadvantage as the system described above. Here as well more costs can occur, due to the hinge connection which has to be incorporated in the hub.

Onshore or offshore

The recommendation here is to go onshore for a turbine of 500 kW, because there are some large costs involved when going offshore. Among other contributions to the higher costs one must point out for example the costs related to towing-boats for the installation and the implementation of the grid connection, which together make a small turbine less interesting. Therefor wind parks in combination with large wind turbines are more suitable for offshore projects.

Coning

For a downwind configuration, coning of the rotor can be a good option, Prof. Dr. Ir. G.A.M. van Kuik appears to be a recommended source.

6-2-5 Ir. W.E. de Vries, CT Offshore Constructions

At the TU Delft, a lot of development is aimed at offshore foundations because most of the innovative possibilities for the foundation are offshore. During the interview de Vries explained some trade-off factors between onshore and offshore and he explained what kind of factors influence the choices of several offshore foundations.

1. Offshore is not attractive for a 500 kW wind turbine because the wind turbine is small and the expenses are not linear with the size. The offshore construction costs are large for both, small and large wind turbines. Also the weather is important for offshore construction and the human safety factor is an important issue.
2. The depth of water around the Netherlands is about 20 m.
3. Deflection of the tower is about 1 m in bad weather.
4. For an offshore construction the forces of the wind and the waves are important.
5. An important reason to go offshore is because most large cities are close to the sea and these cities want power plants close to them. Offshore is therefore an obvious solution because the land is crowded and people don't want a wind turbine in their backyard.
6. Concrete is not common for offshore constructions because steel has better qualities. But steel is much more expensive than concrete, therefore the TU Delft is investigating how to implement more concrete into wind turbine projects.
7. The foundation and tower are drilled mostly about 25 m into the ground and with 20 m of water depth this results in a 45 m foundation.

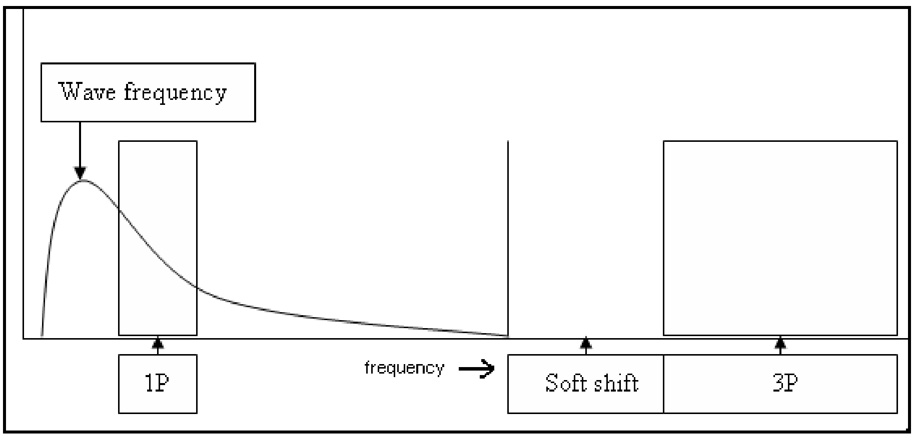

Figure 6-2: Frequency of waves compared to wind turbine towers

8. Figure 6-2 shows the frequency of the waves (the curve) and the frequencies of a single blade (1P) and a triple blade (3P) wind turbine tower. To prevent flutter it is not advisable to produce the wind turbine tower around the same frequency as the waves.
9. Fatigue is very important in the 1P and 2P area. In the 3P area it is not very important.
10. A complying tower means that the eigen frequency of the tower is so low that it occurs before the eigen frequency of the waves.
11. Floating is not attractive because it is mostly for deep water locations and it will cost a lot of energy to keep the rotor stable. It is also difficult to make sure that the rotor doesn't hit the tower.
12. Ampelmann can be used for operation platforms and maintenance.
13. The tower is moulded to the foundation with a special kind of concrete.
14. Anodes and aluminium coatings are added at the surfaces to prevent corrosion.
15. A platform and a ladder are needed for maintenance and inspection.
16. Cables are directed with a flexible tube.

6-2-6 Software resources

1. Wave program to calculate the effect of waves.
2. Models for forces on foundations by ground movements: 'Ensys'. M. Zaaijer is working with this program.
3. 'Blades' is a simulation tool for wind turbines.

6-2-7 Possible paper resources

1. Offshore hydromechanics: J.M.J. Journe and W.W. Masse
2. UPWIND (in possession of de Vries and some chapters already in our possession)

Chapter 7

Design Option Tree

7-1 Selection of concepts

The objective of this phase of the project is to generate a limited number of feasible and promising concepts for the innovative wind turbine, as part of a research tool.

The concepts are based on the technical requirements and the constraints as generated in the requirement discovery tree diagram. The selected concepts within this stage are to be optimised and designed in more detail in the follow up stages.

Next to a more systematic approach to obtain the objective of this task, a more intuitive selection has been made in order to have sufficient variety in the concepts. The systematic approach is based on a functional breakdown structure of the system. In this functional breakdown, a systematic picture is generated of the different functions of the complete wind turbine system. Subsequently possible solutions have been generated for the different functions, the interactions of the different functions have been mapped and feasible combinations have been selected.

Since it can be expected that for all types of wind turbines the availability will be a major factor in determining the final energy yield and costs, a delicate balance between this fact on the one hand and the innovative aspects of the design concept, on the other has been used as a major selection criterion.

In order to obtain more qualitative data on technical innovations developed in the TU Delft, professors, engineers and Ph.D. students have been visited; however, because of the vast and variable amount of topics that are involved in the design option, these visits have not yet produced useful results at this phase. Several brainstorm sessions with the team members have been held in order to produce an indication of the potential integrations of the different in-house available innovations in the design.

7-2 Function

Based on an extensive functional breakdown, the major functions of a wind turbine have been defined and possible system options to fulfil this function are listed. The interactions of these system choices have been therefor described below.

The following definitions of different kinds of interactions have been used in the categorisation:

- Exclusive interaction: excludes the choice of any other concept.
- Major Interactions: determine the choice for a certain option.
- Minor interactions: influence the choice for a certain option.

Where possible, the phase in the design process where the final choice for a certain system option has to be made is indicated.

The following phases have been distinguished:

- Conceptual design: For all functions a feasible option has been selected fulfilling all boundary conditions such as interactions
- Pre design: All options have been specified to such level that a complete load-set can be generated (system specifications)
- Detail design: Specification in detail of all parts required for each function.

7-3 Tower

The design option tree of the tower is shown in Appendix D-1

7-3-1 Function

Assure proper elevation and proper position in space of other systems.

7-3-2 Possible options

- Lattice structures, guyed
- Lattice structures, not guyed
- Closed structure with the yaw control system at the nacelle, with circular or square cross section, guyed
- Closed structure with the yaw control system at the nacelle, with circular cross-section, with or without a boundary layer transition strip, square cross section or a rotating shell around the support structure, not guyed
- Closed structure with the yaw control positioned lower in the tower, with an airfoil shaped cross section.

7-3-3 Exclusive interaction

- Foundation. For some offshore structures foundation and tower concepts are exclusive combinations.
- Nacelle, especially when the yaw control is positioned lower in the tower.

7-3-4 Major interactions

- Rotor concepts: The tower bending modes and natural frequencies are depending strongly on the tower concept. The design should be matching with the rotor excitation frequencies and the rotor natural frequencies and modes.

7-4 Nacelle

7-4-1 Function

Assure strength and environmental protection for the drive train.

7-4-2 Description

The Nacelle is the part of the wind turbine between the hub and the tower. The function of the nacelle is to provide strength for the drive train and thereby assure a proper alignment for the hub axis, possibly also the gearbox and generator. The nacelle also provides protection against environmental impact, such as precipitation, wind, bird strikes and lighting. In the case of a down-wind turbine the nacelle also has influences on the rotor performance because the nacelle is placed in front of the rotor. This is especially the case for direct drive generators, because they are much larger than generators with a gearbox. The design option tree of the Nacelle is shown in Appendix D-2.

7-4-3 Possible options

- Load carrying skin
- Casted frame
- Welded frame
- Integrated casted frame with generator and gearbox

7-4-4 Exclusive interaction

- Maintenance: When the nacelle is large enough, maintenance can be preformed inside the nacelle, otherwise the top has to be removed and maintenance has to be preformed on top of the nacelle.
- Installation: Self hoisting options are strongly related to the nacelle.

7-4-5 Major interactions

- Hub and tower: The nacelle is connected to both the tower and hub.

7-5 Electrical machines, drive train and gear box

The electrical machines such as the generator, power converters, drive train and gear box combination could possibly be chosen from an off-the-shelf solution using the requirements. [Wildi, 2006] gives in pages 697-700 some common wind turbine generator types: asynchronous generator, double-fed induction generator. Also some basic concepts about the generator grid connection via power converters are presented. Specialists in the field, such as Ghanshyam Shrestha from the faculty of Electrical Engineering, Mathematics and Computer Science, shall be approached to further gain insights in current and innovative trends. From there the design options for the electrical machines, drive train and gear box combination can be worked out and decided whether or not an off-the-shelf solution can be chosen. Therefor the decision has been taken to momentarily delay the design option tree for this sub-system until further insight has been achieved.

7-5-1 Function

Convert shaft power to electrical grid power.

7-5-2 Possible options

- Direct drive, no gearbox
- small gearbox, bigger generator
- fully geared, generator

7-5-3 Major interactions

- Gearbox (i.e. number of stages, conceptual design)
- Generator layout (i.e. conceptual design)
- Rotor speed
- Grid connection and properties

7-6 Foundation

The design option tree of the foundation is shown in Appendix D-3

7-6-1 Function

Fix a stable position of the wind turbine to the ground.

7-6-2 Possible options

- Offshore
  - Monotower structure
  - Tripod structure
  - Jacket structure: Four large piles which are connected with several smaller piles in a triangular shape (e.g. The Eiffel Tower).
  - Gravity structure: A foundation consisting of a heavy material and a large radius to add a lot of weight on the foundation.
  - Floating structure
  - Suction can: In this construction there are empty holes where the water is sucked out. This will result in a pressure difference resulting in a stable foundation.
- Onshore
  - Monotower structure
  - Platform structure: A large disk for foundation. Looks like the gravity structure with the only difference that this disk is less high and the radius is larger.
  - Tripod structure

The materials used offshore are mostly steel. Concrete is an innovative option because it is cheaper and stronger. The only disadvantage is production at the sea floor. Onshore mostly concrete is used because it is cheap and strong and easy to transport to the location. There are no production problems.

For offshore, a maintenance platform is needed. This will be connected to the support structure. The support structure is the top part of the foundation just above the surface. The maintenance platform is mostly like a balcony but there are concepts of floating platforms.

7-6-3 Exclusive interaction

- Tower: The design of the tower will determine if a Monotower or Tripod design for the foundation might be needed. And the shape of the tower could also determine till what depth the foundation has to be put into the ground.

7-6-4 Major interactions

- Maintenance
- Rotor concepts: The tower bending modes and natural frequencies are depending strongly on the foundation concept. The design should be matching with rotor excitation frequencies and rotor natural frequencies and modes.

7-7 Wind turbine control system

Part one of the design option tree of the control system is shown in Appendix D-4 and part two in Appendix D-5

7-7-1 Function

Measure and optimise the turbine performance and reduce the loads caused by unsteady flows.

7-7-2 Possible options

- Passive control systems
- Active aerodynamic control systems (e.g. flaps, pitch, etc.)
- Active mechanical control systems (e.g. brakes)
- Feedback based systems
- Feed-forward based systems
- Combinations of several

This is a very rough classification of options for the control system. A more elaborate treatment of the different design options can be found in the design option tree.

7-7-3 Major interactions

- Rotor design through control surfaces and actuators
- Generator and drive train through torque and speed settings
- Nacelle design through yaw control system

7-7-4 Minor interactions

- Tower and foundation through the (reduced) loads that have to be led to the ground.

7-8 Rotor

The design options for designing the rotor have been split in to two different option trees. The first part of the design option tree is shown in Appendix D-6, the second part in Appendix D-7

7-8-1 Function

The main function of a rotor is to convert kinetic energy from the wind into mechanical energy and to transfer the loads to the surrounding structure.

7-8-2 Possible options

- Number of blades (1, 2, 3 etc.)
- Load carrying skin concept for blade construction
- Rib & spar concept for blade construction
- Solid blades
- Use composite materials (Grassfire, glare, carbon, etc.)
- Use metals
- Use polymers

7-8-3 Exclusive interaction

- None

7-8-4 Major interactions

- Drive train and main shaft have an interaction with the rotor through the torque and rotational speed.
- The tower has multiple interactions with the rotor. The loads that are coming from the rotor have to be lead to the foundation and also the wake, that is produced by the tower, has a major influence on the rotor loads (unsteady flow field).

The design option tree for the rotor subsystem shows the major design choices that have to be made during the rotor design. Three major design choices were already made by the customer, namely; a down-wind configuration, single rotor and horizontal-axis configuration. Therefor, these design options are not further mentioned in the design option tree.

Design choices that are stated in the design option tree comprise for instance of the number of blades from which the rotor is built up, but also the structural blade design and the material selection. The aerodynamic part of the blade design is something that is not taken into account in this design option tree stage because of the large number of aids available for the aerodynamic design optimization. For instance there are design parameters like the sweep angle, the aerodynamic twist angle, the taper ratio, the specific airfoil distribution, the vortex generators, the low-noise tip design, etc. Putting all these aids and their possible combinations in the design option tree would result in an enormously extensive tree, which is unpractical to use. In the detailed design effort these aerodynamic issues will be addressed extensively.

Chapter 8

Resource Allocation

8-1 Weight

The average total weight of a 500 kW onshore wind turbine is about 50 tons. This weight can be divided over the different parts as shown in table 8-1. For offshore wind turbines a much larger foundation and a higher tower elevation is needed due to the water level, so the total weight will be much higher.

Table 8-1: Weight breakdown [Ancona and McVeigh, 2001]

Component	% of machine weight
Rotor	10-14
Nacelle and Machinery	25-40
Gearbox and Drive Train	5-15
Generator Systems	2-6
Weight on the Tower	35-50
Tower	30-65

8-2 Size and height

The rotor has to be placed as high as possible into the air because the wind speed is larger at higher altitudes. Since the maximum output of 500 kW is a given requirement, the size of the blades can be constructed smaller at higher altitudes. The size of the blade is usually between 16.5 m and 20 m so the total rotor span is about 33 m to 40 m. The height of the tower depends on several aspects;

- the tower cost per meter
- the wind speed rate changes with height
- the price the owner gets for one kWh

This results in a height between the 50 m and 70 m.

8-3 Separation between wind turbines

A thumb rule for the distance between wind turbines is that the distance is 5 to 9 times the rotor diameter in the prevailing wind direction and 3 to 5 times the rotor diameter perpendicular to the prevailing wind direction.

8-4 Environment conditions

The ambient conditions in which the turbine is running are

- Temperature range of -20 up to +50
- Maximum solar radiation 1,000 W/m^2
- Air density 1.13-1.35 kg/m^2

8-5 Tip speeds

On land the tip speeds vary between about 50-75 m/s. Higher values is in most cases not possible due to sound emission issues. For this reason the tip speeds of offshore turbines can be slightly higher.

8-6 Noise

The noise production of the wind turbine is usually between the 90 dB and 100 dB this will result in to about 35 dB to 45 dB at 350 m distance.

8-7 On-Board sensors

An efficient computer is needed to make sure that the wind turbine is able to adapt the blades to get the optimal position compared to the wind direction and speed. The performance measurement system in this computer should at every moment measure and log the performance and status of the wind energy conversion system. Also the capacity should be able to work full automatic. The wind speed and direction could be measured with an anemometer. For commercial wind turbines a 1% accurate anemometer is frequently used.

8-8 Maintenance

Maintenance not related to research should be limited to once per two years. The wind turbine also has to incorporate self-maintenance strategies to reduce to maintenance operation frequency.

8-9 Power coefficient

The power coefficient is the coefficient resembling the amount of power being converted by the rotor from the wind into mechanical energy. The current wind turbines have a power coefficient in the bandwidth between 0.45 and 0.50. The aim for our design is at the top of this range.

8-10 Capacity factor

The capacity factor is the ratio between the total annual energy yield that would be obtained when the turbine is running the whole year on its rated power and the actual annual energy yield. The current wind turbines have a range of capacity factor between 0.20 and 0.70, but most of them fall between 0.25 and 0.30.

8-11 Gearbox ratio

For direct drive turbines there is no gearbox so then the ratio is 1. A typical used gearbox ratio for a three blade large wind turbine is about 50, but there are many variations on this, so the range of gearbox ratios for geared driven wind turbines is from 25-75.

Chapter 9

Project Cost

The project costs of a wind turbine can be divided in several distinct areas. The project cost itself has two main influencing areas: the cost per installed kW turbine power and the operational costs. These will determine the total expenses for the project. Furthermore one has to account for an interest rate that has to be paid in case of a loan, which would probably be necessary due to the relatively high investment costs. On the other hand there is the electricity that is produced by the wind turbine and which can be sold to customers in order to make the necessary profit to pay back the loan.

9-1 Installation cost

The installation costs have the largest contribution to the total project costs. They cover the manufacturing costs, the research costs, the development costs and the site related costs. This price is defined per kW installed wind turbine. According to the requirements stated in the project guide, the current cost is €1000 per installed kW. Applying this to a wind turbine with a rated power of 500 kW, the following installation price is obtained:

$$1,000 \cdot 500 = 500,000 \; euro \tag{9-1}$$

In this price the operational costs and the interest rate are not yet included, these are mentioned in the next paragraphs.

9-2 Operational costs

The operational costs include the day to day operation costs of the wind turbine and the scheduled and unscheduled maintenance. According to the project guide the current operational costs are €39 per kW per year. For a wind turbine with a rated power of 500 kW the following calculation can be made:

$$39 \cdot 500 \approx 20,000 \; euro \tag{9-2}$$

9-3 Interest costs

In most cases a loan is necessary to finance a project of such a scale. An annual interest rate of 5% is assumed for this project. This number represents the"real interest rate" (r) which can be calculated using equation 9-3 using the inflation (v) and the bank interest rate (i).

$$1 + r = \frac{1 + i}{1 + v} \tag{9-3}$$

To value the wind turbine over the future, the revenues have to recalculated for the present time. This means compensating for the real interest rate. in section 9-6 it can be seen how this is done. At this point it is worthy to know that early revenues are more significant because of the inflation.

9-4 Wind turbine performance

The wind turbine performance that is of importance here, is the annual energy yield computed for a certain site. The site that was chosen is described in the wind resource assessment document in further detail. Table 11-1 mentions the annual energy yield for the specified site.

Table 9-1: Yearly energy yield at different operating regimes in 10^6 kWh

Operating range	95%	96%	97%	98%	99%
on-shore	1.0804	1.1227	1.1658	1.2109	1.2553
off-shore	1.5381	1.5880	1.6281	1.6731	1.7166

This annual energy yield is dependent on the efficiency of the wind turbine, so this will heavily influence the cost of the delivered power. For further calculations the operating range is assumed to be 99% and the accompanying annual energy yield is approximately 1,260,000 kWh.

9-5 Revenue

In the requirements was stated that the price per kWh should aim at 92.5% of a conventional wind turbine and this was set to €0.07 per kWh. The revenue that the wind turbine delivers per year can now be calculated and will be:

$$0.925 \cdot 0.07 \cdot 1,260,000 \approx 82,000 \; euro \tag{9-4}$$

9-6 Cost-revenue-interest calculations

Reference [Timmer, 2006] provides a method of calculating the net present value (NPV) of a wind turbine (equation 9-5), using all payments and revenue, counting back to the initial loan.

$$NPV = \sum_{t=1}^{T} \frac{(S_t - C_t)}{(1+r)^t} \tag{9-5}$$

where:

- C_t = costs in year t
- S_t = revenue in year t
- r = real interest rate
- T = wind turbine lifetime

The values that are used can be found in table 9-2

Table 9-2: Project costs variables

Production price per installed kW	1,000	€/kW
Rated power	500	kW
Interest rate	5.00	%
Revenue per kWh	7	€ct
Price factor	0.925	-
Maintenance & operations costs	39	€/year/kWh

As only in the first year the costs differs, it is possible to write (9-6):

$$NPV = -500,000 + \sum_{t=1}^{T} \frac{(82,000 - 19,500)}{(1+r)^t} \tag{9-6}$$

The results of a 5% interest rate can be found in the following table: table 9-3.

Another way of doing the same calculation is to separately calculate the value of the wind turbine for every year as an iterative process. So the value in year 0 V_0 is €-500,000 and for year 1 value v_1 equation 9-7:

$$V_1 = \frac{(V_0 + (82,000 - 19,500))}{(1+r)} = \frac{(-500,000 + (82,000 - 19,500))}{(1+r)} \approx -460,000 euro \tag{9-7}$$

And for year 2 (equation 9-8):

$$V_2 = \frac{(V_1 + (82,000 - 19,500))}{(1+r)} = \frac{(-460,000 + (82,000 - 19,500))}{(1+r)} \approx -420,000 euro \tag{9-8}$$

Or for year T (equation 9-9):

$$V(T) = \frac{V_{T-1} + (82,000 - 19,500)}{(1+r)} \tag{9-9}$$

However, this is the value progressing with time, so not the real present value. In order to obtain the real present value one applies equation 9-10.

$$NPV(T) = V(T) \cdot (1 + r) \tag{9-10}$$

The result is the same as the last column of table 9-3.

Table 9-3: Net Present Value calculations with 5% interest rate

T (year)	Sum of net present profits $\sum_{t=1}^{T} \frac{(82{,}000-19{,}500)}{(1+r)^t}$	Net present profit $\frac{(82{,}000-19{,}500)}{(1+r)^t}$	Net Present Value (NPV) $-500,000 + \sum_{t=1}^{T} \frac{(82{,}000-19{,}500)}{(1+r)^t}$
0	€0	€0	€-500,000
1	€59,000	€59,000	€-440,000
2	€56,000	€110,000	€-390,000
3	€53,000	€170,000	€-330,000
4	€51,000	€220,000	€-280,000
5	€48,000	€270,000	€-230,000
6	€46,000	€310,000	€-190,000
7	€44,000	€360,000	€-140,000
8	€42,000	€400,000	€-100,000
9	€40,000	€440,000	€-60,000
10	€38,000	€480,000	€-20,000
11	€36,000	€510,000	€13,000
12	€34,000	€550,000	€48,000
13	€33,000	€580,000	€80,000
14	€31,000	€610,000	€110,000
15	€30,000	€640,000	€140,000
16	€28,000	€670,000	€170,000
17	€27,000	€700,000	€200,000
18	€26,000	€720,000	€220,000
19	€24,000	€750,000	€250,000
20	€23,000	€770,000	€270,000
21	€22,000	€790,000	€290,000
22	€21,000	€810,000	€310,000
23	€20,000	€830,000	€330,000
24	€19,000	€850,000	€350,000
25	€18,000	€870,000	€370,000
26	€17,000	€890,000	€390,000
27	€17,000	€900,000	€400,000
28	€16,000	€920,000	€420,000
29	€15,000	€940,000	€440,000
30	€14,000	€950,000	€450,000

9-7 Total investment scheme

According to the previous calculations each year an amount of €62,000 can be paid back (not counting interest). If one looks at table 9-3, it can be concluded that the total investment amount and the interest cost can be paid back in 11 years and that the wind turbine is profitable after that period of time. One can also conclude that after 25 years, the amount of profit that can be made will be approximately €370,000.

As stated in section 9-3, the revenue in the first years is more significant than at the end of the operation time of the wind turbine, as the graph is more steep at the beginning. Note that after break-even is achieved, the bank interest does not have to be payed anymore. This effect is not taken into account, because the calculation of the 5% real interest rate is too complicated to be incorporated at this time. As interest and inflation are depending on each other it is safer to say the fraction stated in equation 9-3 is constant than to predict future inflation. Also, as this is a very early model, the effects of changing interest might not be significant at all.

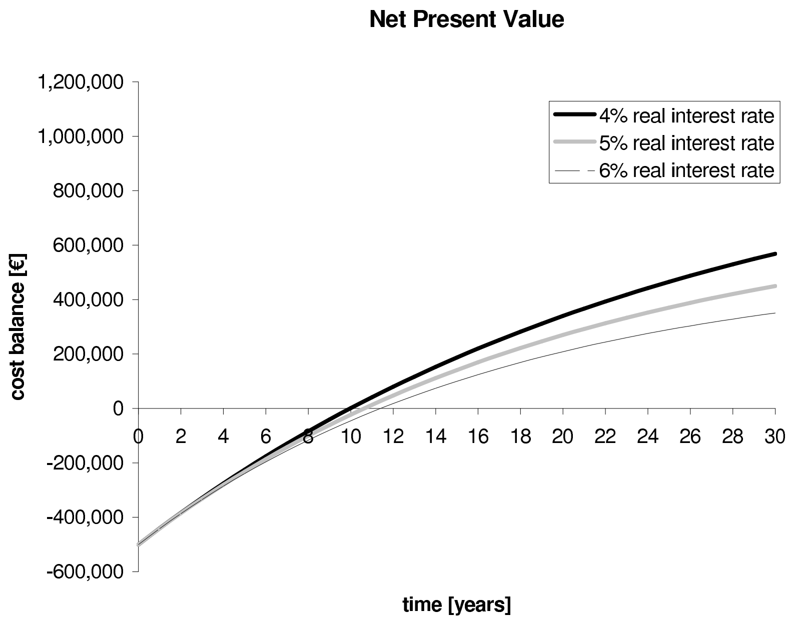

Figure 9-1: Cost scheme

Chapter 10

Technical Risk Assessment and Risk Map

10-1 Risk assessment

Designing a standard wind turbine of a relatively small size such as a 500 kW wind turbine, can be considered to be a proven process. Today, larger and more powerful machines are common. So it can be stated safely that the highest risks are not situated at the actual design process itself, but at finding, understanding and incorporating new and innovative designs options.

Have said this, the new challenge appears when evaluating whether or not all these new concepts and technologies would meet the constraints and requirements in the actual design process. This implies that the risk of finding, understanding and incorporating new innovative concepts will be multiplied, (two risk factors in series) with the risks of designing the actual concepts within the given constraints.

The fact that the project design team is not composed of specialists in the relevant scientific fields which could have made a drastic difference when incorporating new technologies, should clarify that risks are relatively high compared to the actual well documented design process. The relatively high risk however should not be exaggerated since the project is hosted within a well rated university and supported by several scientific specialists in the relevant fields.

It should be mentioned that in this stage of the project, qualifying the risks of the different components that are to be designed, is a difficult task. Before this can be done accurately, more has to be found out about the actual different innovative design options. As always, building based on a prototype approach will never be as confident as building based on an all proven design concept and known production processes. Hence, in the risk map illustrated in table 10-1, some particular risks are for a large extent qualified only approximately.

10-2 Risk map

All the concepts and technologies to be applied are placed in the risk map shown in table 10-1. The categories in the left column indicate the technology status. In other words, they must be considered as the chance of the successful functioning of a certain technology. The bottom row shows the impact on the overall design if the technology fails. So the risk -product of the consequence of occurrence against the probability of occurrence- runs from zero in the lower left corner, to very high in the upper right corner. Note that this risk map only includes actual requirements and subsystems, not the actual design process and the information acquisition.

Table 10-1: Risk Map

Probability of failure					
	Feasible in theory				2, 9
	Working laboratory model		11	6, 10, 13	1, 5
	Extrapolated from existing designs			12	
	Proven design		7, 8	3, 4	
		Negligible	Marginal	Critical	Catastrophic
		Consequence of failure			

Elements regarding the actual design of the wind turbine:

1. Smart rotor devices
2. Fatigue and vibration resistant materials
3. Power control
4. Power conversion system
5. Low maintenance design
6. Economically viable
7. Foundation
8. Installation
9. Fatigue and vibration reducing systems

10. Incorporating smart materials
11. Minimal noise design
12. Easy recycling material properties
13. Smart production and assembly process

The budget breakdown is a tool for distributing the total available financial resources over the different project parts. In a wind turbine project the total costs can be divided over the one-time investment costs and the operational costs. Furthermore the one-time costs can be then broken down into several parts which will be mentioned further in the text. From all these parts the wind turbine costs are considered as the largest part and these can be split up into the costs of the subsequent subsystems. In the following paragraphs this whole breakdown will be discussed in detail.

Table 10-2: Budget breakdown 500 kW wind turbine

	cost percentage	absolute costs
One-time investment costs (51 %)	51 %	€500,000
Operational costs (49 %)	49 %	€487,500
One-time investment costs		**€500,000**
civil works (13 %)	13 %	€65,000
electrical infrastructure (8 %)	8 %	€40,000
grid connection (6 %)	6 %	€30,000
project management (1 %)	1 %	€5,000
installation (1 %)	1 %	€5,000
insurance (1 %)	1 %	€5,000
legal costs (2 %)	2 %	€10,000
bank fees (1 %)	1 %	€5,000
interest during construction (2 %)	2 %	€10,000
development costs (1 %)	1 %	€5,000
wind turbine (64 %)	64 %	€320,000
wind turbine		**€320,000**
Tower (26 %)	26 %	€83,200
Rotor (28 %)	28 %	€89,600
Nacelle & Controls (22 %)	22 %	€69,440
Gearbox & Drive train (17 %)	17 %	€55,360
Generator & Power electronics (7 %)	7 %	€22,400

10-3 Main cost breakdown

As already mentioned before the costs of the total wind turbine project can be split up in two major parts: on one hand the one-time investment costs and on the other the operational costs. The one-time investment costs consist of the whole investment that a customer has to make at the beginning of such a project. These consist of several subparts that will be explained later on. If it is assumed that the current investment costs are €1,000 per installed kW, then the one-time investment costs for the 500 kW turbine will be €500,000. For the operational costs a price of €39 per installed kw per year was assumed, thus if a lifetime of 25 years is taken into account, the total operational costs will amount to approximately €490,000. This first breakdown is visualised in figure 10-1 where also the percentage distribution is reflected. Both the percentage distribution and the absolute costs are represented in table 10-2.

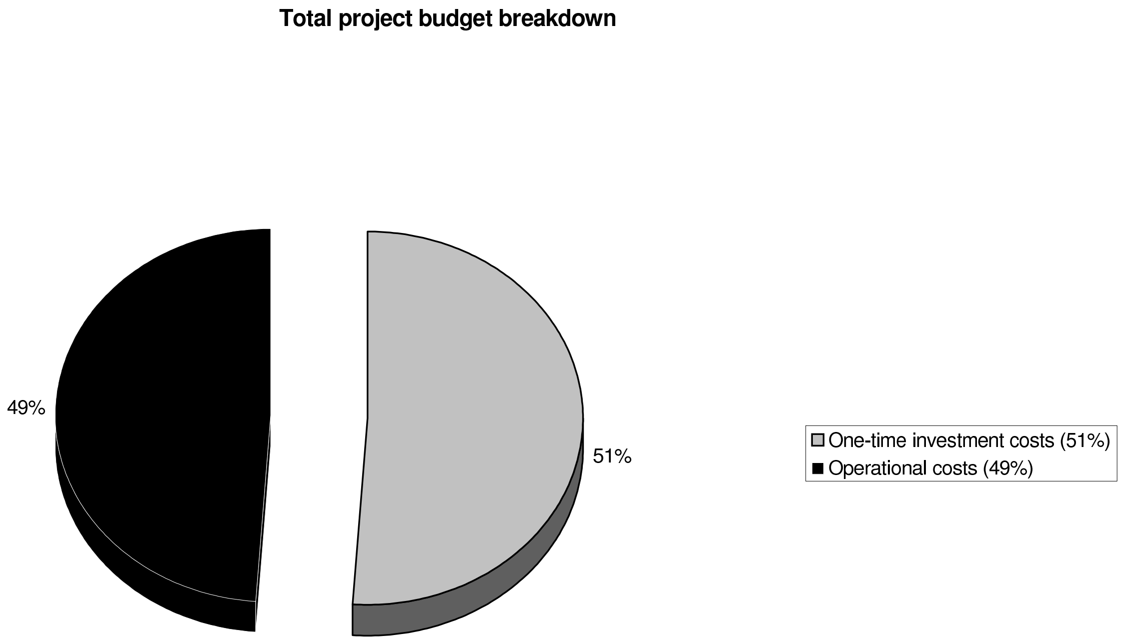

Figure 10-1: Total project budget breakdown chart

10-4 One-time investment cost breakdown

The one-time investment cost can be divided into several parts:

- wind turbine costs
- civil work costs
- electrical infrastructure costs
- grid connection costs
- project management costs
- installation costs
- insurance costs
- legal costs
- bank fees
- interest during construction
- development costs

The more detailed breakdown where the percentages are shown, can be seen in figure 10-2. This breakdown was used by the British Wind Energy Association (BWEA) for a 5 MW onshore wind turbine project. For a 500 kW project the percentage distributions will be a little different because the importance of several cost components will increase or decrease accordingly, but as a first approximation this will be the rough percentages that will be used for the breakdown structure. For example the relative cost of the wind turbine itself will decrease because a 500 kW turbine is a currently proven and standard design compared to a 5 MW turbine and thus it will cost less in comparison to other one-time cost sub-parts. while the civil work costs will on the other hand be a larger contribution to the total one-time investment cost. Also the electrical infrastructure together with the grid connection costs will become a more important part of the total one-time investment costs for a smaller wind turbine. So the major relative percentage redistribution will take place in the 4 sub-parts mentioned above. While the other parts will remain approximately the same, mainly due to their relatively small contribution in the one-time investment cost.

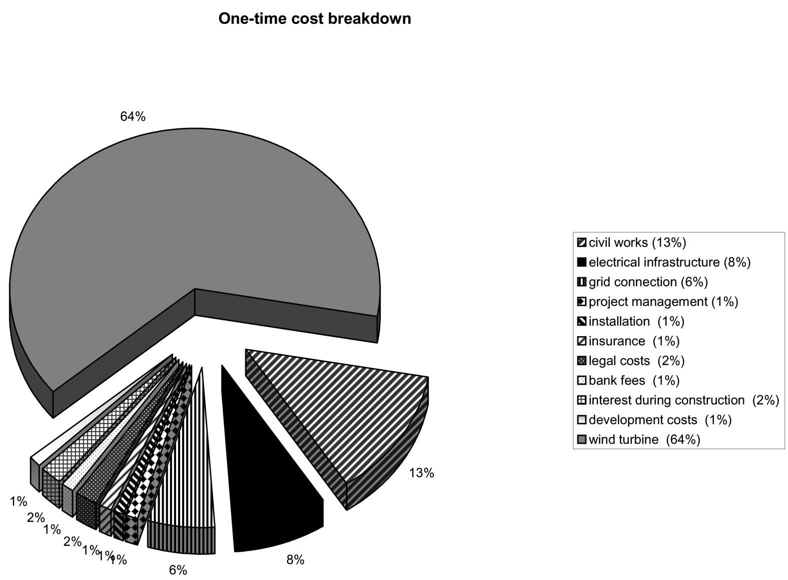

Figure 10-2: One-time investment cost breakdown chart

10-5 Wind turbine cost breakdown

The largest part of the one-time investment cost consists of the wind turbine costs itself. These can be further sub-divided in the costs of the subsystems. According to the Renewable Energy Policy Project the division can be made in the following systems: the tower, the rotor, the nacelle & controls, the gearbox & drive train and finally the generator & power electronics. Their percentage distribution can be seen in figure 10-3, and both the percentages and the absolute cost distribution is apparent in figure 10-2.

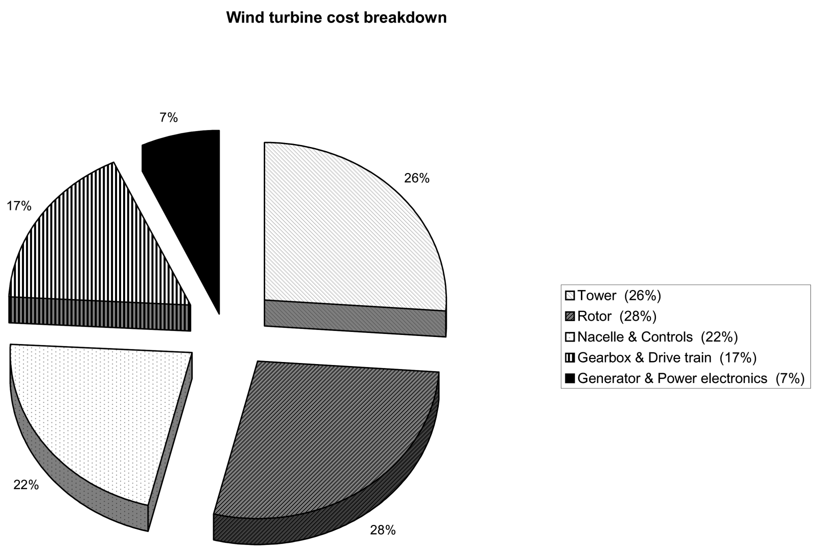

Figure 10-3: Wind turbine cost breakdown chart

10-6 Operational costs

The wind turbine operational costs are the second largest contributor to the total project costs as can be seen in figure 10-1 and therefor they are a important part to be considered. These costs include, the day to day operation of the wind turbine, the scheduled and unscheduled maintenance, the reparation costs and much more. Taken individually they don't give a large cost every year, but due to the fact that they are recurring each year until the end of the lifetime of the turbine, they add up to a very large sum. So in order to reduce the total costs of the project, one also has to look in to reducing the operational costs and not only the one-time investment costs.

Chapter 11

Annual Energy Production Estimation

In order to do a proper cost analysis, a rough estimation of the energy production is necessary, since the yearly energy production has a major influence on the kWh price. To do such an assessment, one first has to pick a geographical site for the turbine to be placed, so the availability of wind power can be derived from meteorological data. In order to do a complete cost estimation, both an onshore site and an offshore site are taken into account. Some assumptions have to be made on the power curve, namely the relation between wind speed and power produced by the turbine.

11-1 Site selection and wind resource assessment

As mentioned earlier, both an onshore and an offshore site are selected, both within the Dutch borders. The onshore site is the ECN test field at Wieringermeer. Figure 11-2 shows the position of the turbine, figure 11-1 shows the wind speed distribution on that site.

The offshore site that is selected is known within ECN as K13 Alpha, as shown in 11-3.

The data about the wind conditions at the offshore site are provided by the ECN in the form of two Weibull parameters, k and a. These parameters fix the Weibull wind speed distribution. The distribution is plotted in figure 11-4.

11-2 Power curve estimation

The second step in evaluating the predicted energy production is the generation of the power curve, that is the relation between wind speed and produced power, for the

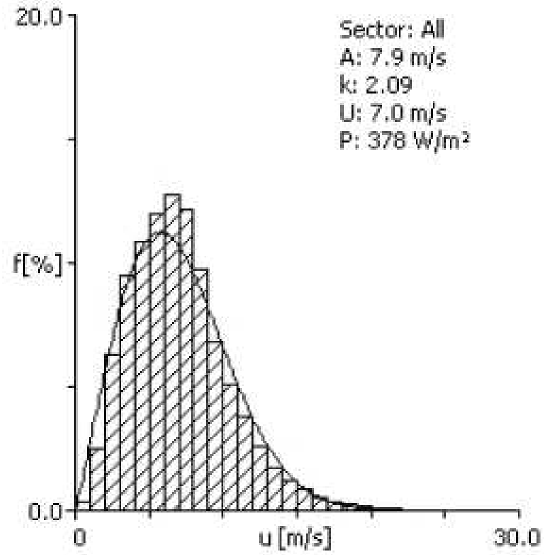

Figure 11-1: Wind speed distribution at Wieringermeer (h=71.6 m)

Figure 11-2: Geographical position of the ECN test site at Wieringermeer

particular wind turbine considered. However, since the turbine has yet to be designed, the best one can do is assume a power curve. As basis for this estimation some parameters from the requirements are used, others are assumed.

The general form of a power curve, for now assuming 100% efficiency after the rotor, is fixed by three parameters: cut-in wind speed, rated power and cut-out wind speed. Starting at cut-in wind speed, the energy production increases with the cube of the wind speed, until rated power is reached. From there, the produced power remains at the rated value with increasing wind speed until the load on the structure forces the rotor to be stopped to prevent catastrophic failure. From this it can be seen that the power curve is strongly dependent on the cut-out speed dictated by the overall structure, which again means that the energy production is also strongly dependent on those structural limits. Therefor, different values for the produced power can be calculated for different cut-out speeds, expressed in terms of percentage of the wind speed regime at which the turbine can be operated. For the case of a turbine operating in 99% of the wind regime, the

Figure 11-3: Geographical position of the K13 Alpha site in the Dutch North Sea

power curve is shown in figure 11-5. Multiplying the power curve with the wind speed distribution, yield the yearly energy produced per wind speed, as shown in figure 11-6. Integrating this curve over the wind speed regime from cut-in to cut-out wind speed, yield the yearly energy production of the turbine. For these calculations, the power coefficient c_p is assumed to be 0.5, which is for now acceptable taking into account that for conventional turbines the c_p ranges between 0.45 and 0.50 [Timmer, 2006]

11-3 Calculation of yearly energy production

Because of the major influence of the operational wind speed regime on yearly energy production, the calculation is performed on different operating regimes ranging from 95% to 99% of the total wind speed regime. This is done for both the onshore and the offshore location, the results are shown in table 11-1.

Table 11-1: Yearly energy yield at different operating regimes in 10^6 kWh

Operating range	95%	96%	97%	98%	99%
Onshore	1.0804	1.1227	1.1658	1.2109	1.2553
Offshore	1.5381	1.5880	1.6281	1.6731	1.7166

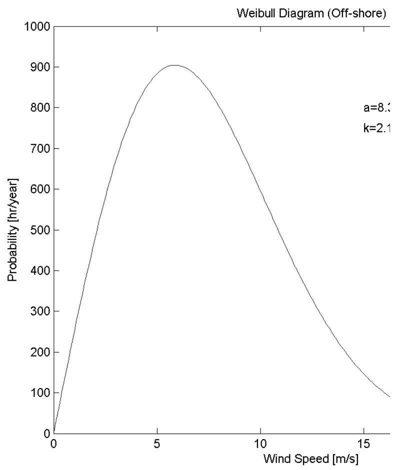

Figure 11-4: Wind speed distribution at the K13 alpha site

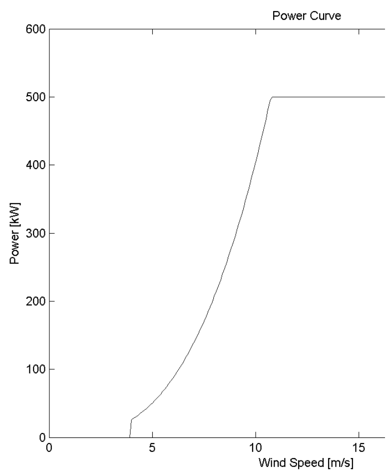

Figure 11-5: Assumed power curve of the wind turbine (turbine operational in 99% of wind speed regime)

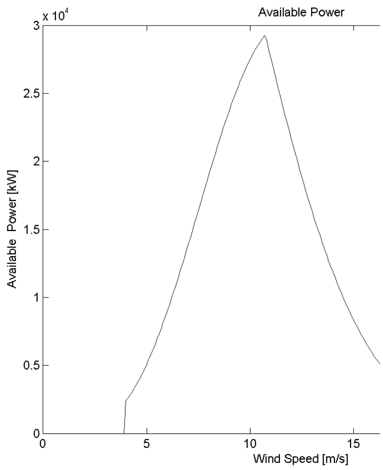

Figure 11-6: Available energy per wind speed (turbine operational in 99% of wind speed regime)

Chapter 12

Sustainable Development Strategy

A wind turbine is a machine that converts kinetic energy (wind) into electrical energy. In comparison to the commonly used chemical reactions using fossil fuels for energy "production", it's mayor benefit is that no greenhouse gasses are produced. Many climate-conscious governments have therefore included wind turbines in their plan to diminish greenhouse gas emissions. The assumption that the entire life time of a wind turbine passes without any emissions however, is false.

12-1 Life cycle

As the function of a wind turbine is to convert energy without greenhouse gas emissions, that part of its life cycle (figure 12-1) is sustainable. The other stages should be analysed separately. For conventional wind turbines the operation time needed to produce the energy that was used to produce (and decommission) the wind turbine is 2 to 3 months (reference [unknown, 2006]). Although this wind turbine is going to be highly innovative, and a high energy production is assumed, it is also a study object, which means different configurations are tried every year or so. For these different configurations more parts need to be produced, thus more energy is needed. While taking both effects into account, an energy payback period of 3 months is assumed. When operation for 25 months, thus 300 months, the energy needed for production is reproduced 100 times.

12-2 Sustainable development target triangle

Apart from environmental issues the word sustainable comprises two other aspects (figure 12-2):

- Economic stability and equality
- Social acceptability

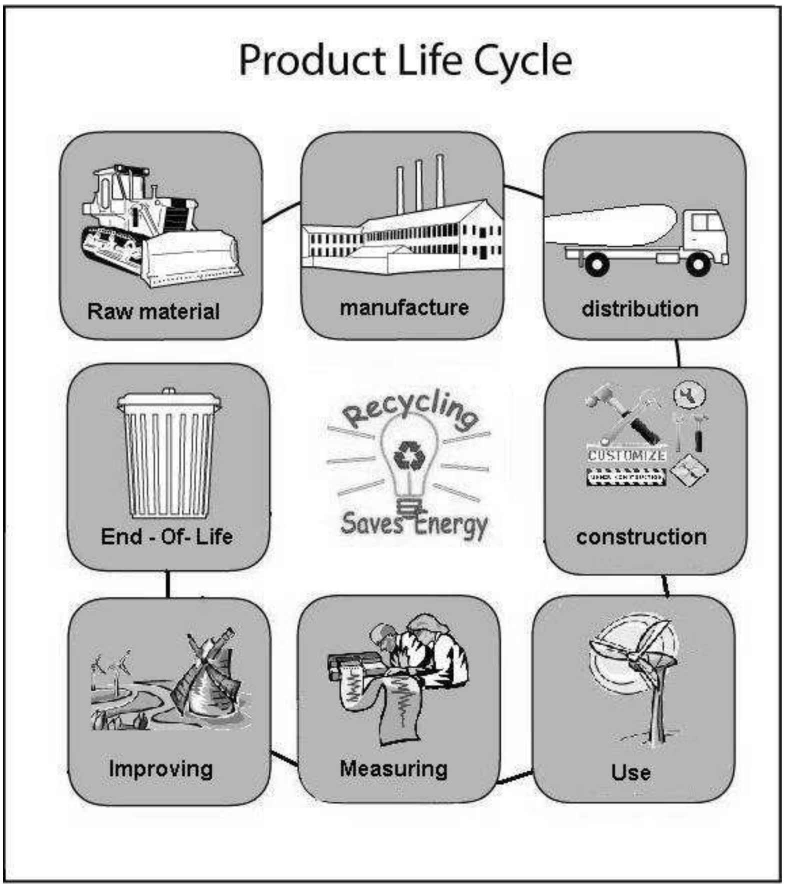

Figure 12-1: The product life cycle, reference [Ordie, 2007]

This means that a product can not be sustainable, if it can not contribute to stability on the financial markets. For example: substituting all fossil fuel power plants with solar and wind energy, if that would mean the oil market would collapse taking with it all depending industries. Especially when millions of jobs depend on it.

It also means that if the people don't want a wind turbine in their back yard because it is too loud, in present or future, it is not a long-term solution, thus not sustainable.

12-3 Materials

The choice of materials is very important as it will have a significant impact on the weight of the entire structure and therefor the loads and the needed amount of supporting structure. The production process also depends on the raw material, and whether or not the product can be recycled. Questions that should be asked are:

- Is it necessary to use materials that harm the environment?
- Are "virgin" materials needed or can recycled or re-usable materials be used?
- Can materials be used that need less energy to produce?

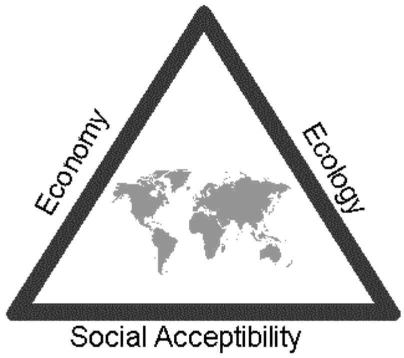

Figure 12-2: The sustainability triangle, reference [Reichel and Semrau, 2006]

In the design the amount of materials used should be minimised. Not just for ecological reasons but also for economical. The following questions should be asked:

- Can the weight be reduced by using less, or lighter materials?
- Can the volume of the product reduced for transportation purposes?

12-4 Production and logistics

Assuming that a chosen production process is already optimized, there is usual a limited amount of processes possible for a part of a certain material. However, it is important to think about re-using the by-products. This makes a process more efficient, such that energy can be preserved.

A good organised logistic process is essential for a sustainable process. The method of transportation should be chosen wisely, as a wind turbine consists of very large parts.

12-5 Operation

During the operating lifetime of a wind turbine the only costs are due to maintenance. This maintenance does not only cost money, but the replaced parts are also produced, usually, using a unsustainable process. During the maintenance, the wind turbine has to be shut down, so that no energy is produced. The minimisation of maintenance is therefor very important. The wind turbine should be able to withstand corrosion and wear.

Of course some maintenance is needed to extend the life of the wind turbine. As the main environmental burden are the production processes, the longer the wind turbine is operational, the higher the profit of the unsustainable produced parts. Therefor the design should be supporting easy access for maintenance and repair.

Wind turbines may be popular due to its sustainable image, it is not always easy to find a place to put the wind turbine. Neighboring people are not always glad to see a wind turbine, therefor esthetics and sound reduction are very important. These aspects should be within a norm for today, but also be accepted over 20 years. Otherwise the turbine might be prematurely decommissioned.

12-6 End-of-life optimization

At the end of the wind turbines life, the wind turbine needs to be decommissioned. As simple as this may seem, there are a few aspects that are to be taken under consideration:

- is it possible to re-use certain parts?
- can the materials be recycled?
- will the incineration create emissions (or waste)?

The end-of-life should already be considered at the design stage. Note that more extensive guidelines for sustainable design can be found at reference [Houtzager et al., 2006].

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Appendix A

Functional Flow Diagram

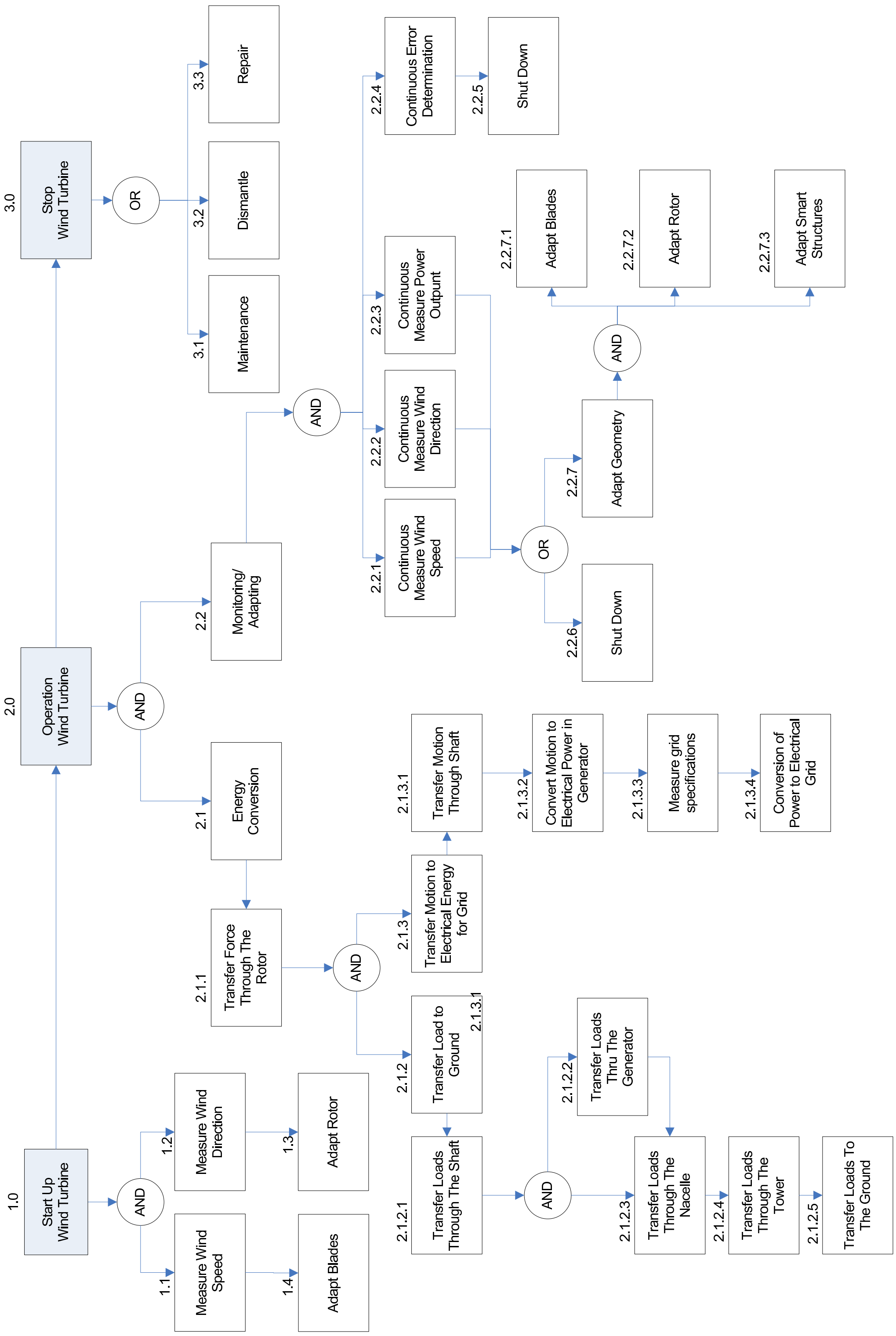

Figure A-1: Functional Flow Diagram

Appendix B

Functional Breakdown Structure

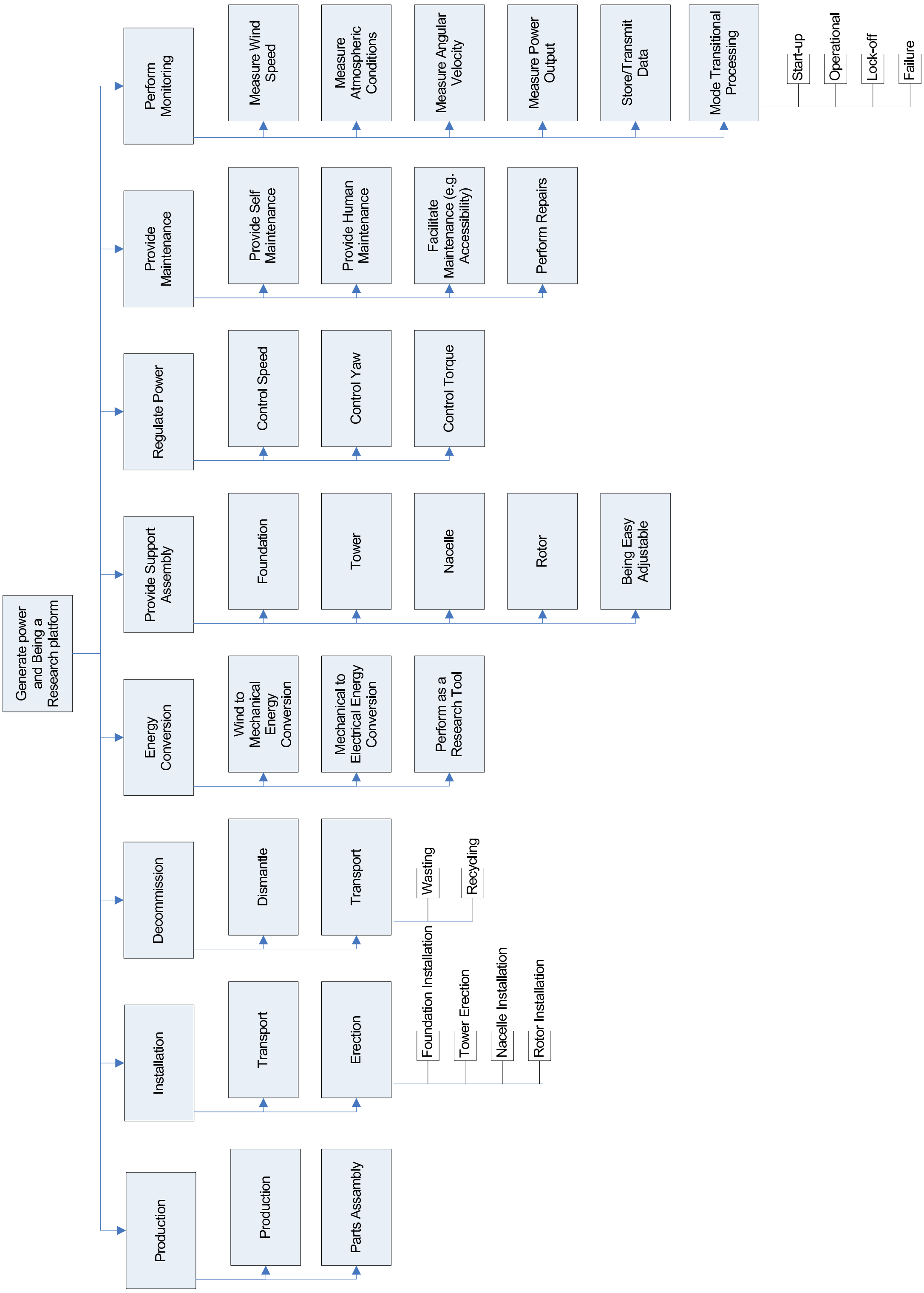

Figure B-1: Functional Breakdown Structure version 2.0

Appendix C

Requirement Discovery Tree

C-1 Requirement Discovery Tree part 1

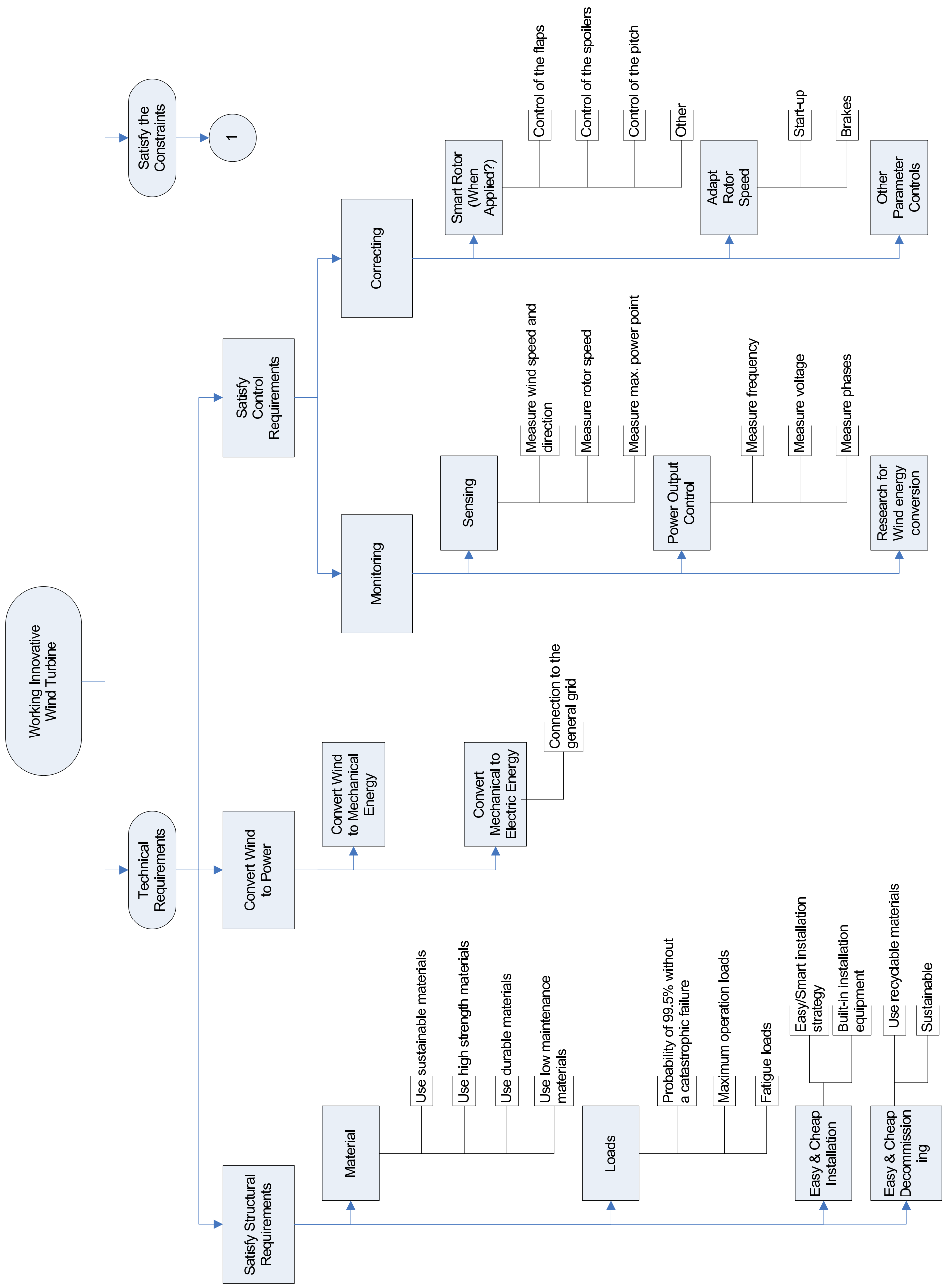

Figure C-1: Requirement Discovery Tree, part 1

C-2 Requirement Discovery Tree part 2

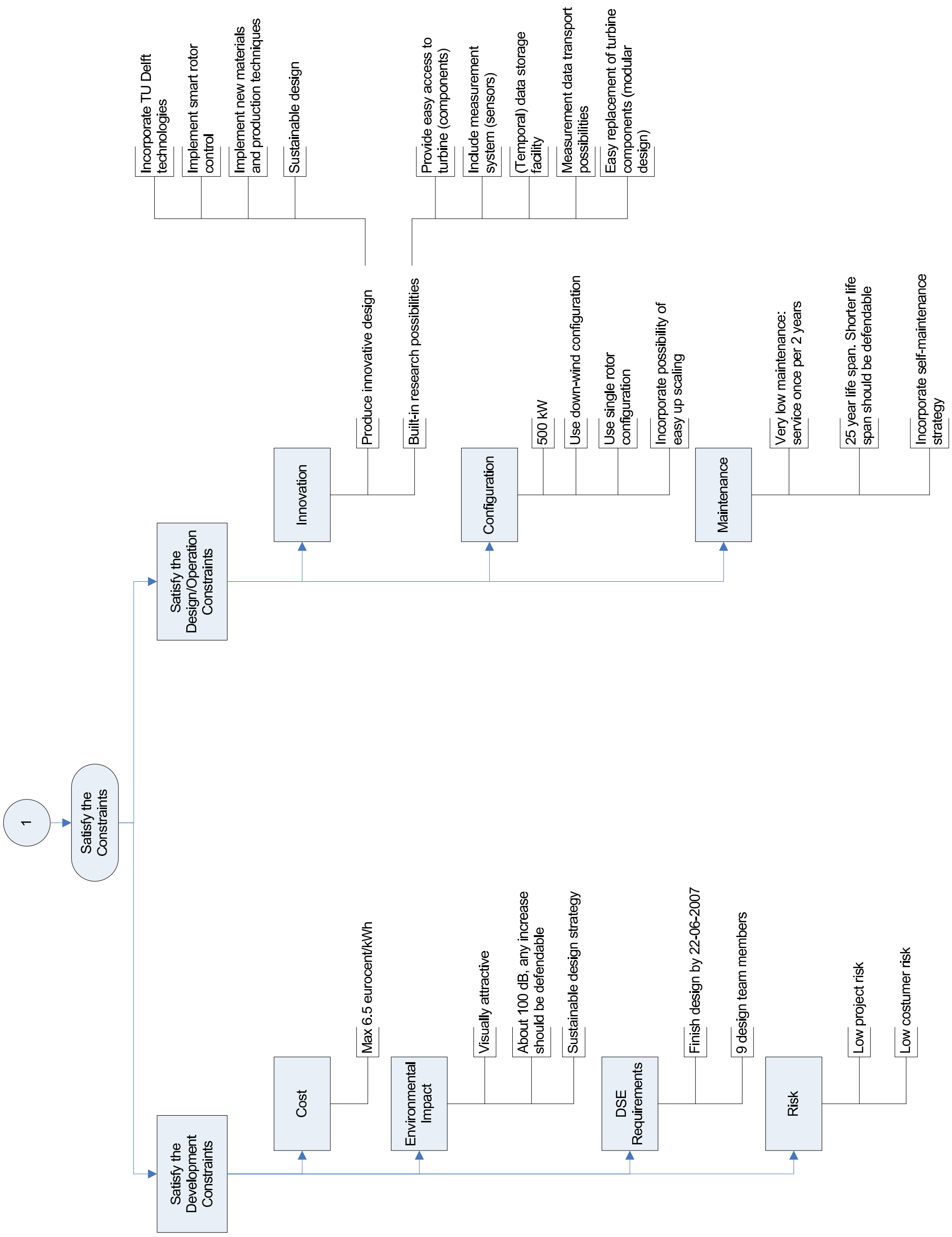

Figure C-2: Requirement Discovery Tree, part 2

Appendix D

Design Option Tree

D-1 Design Option Tree of the Tower

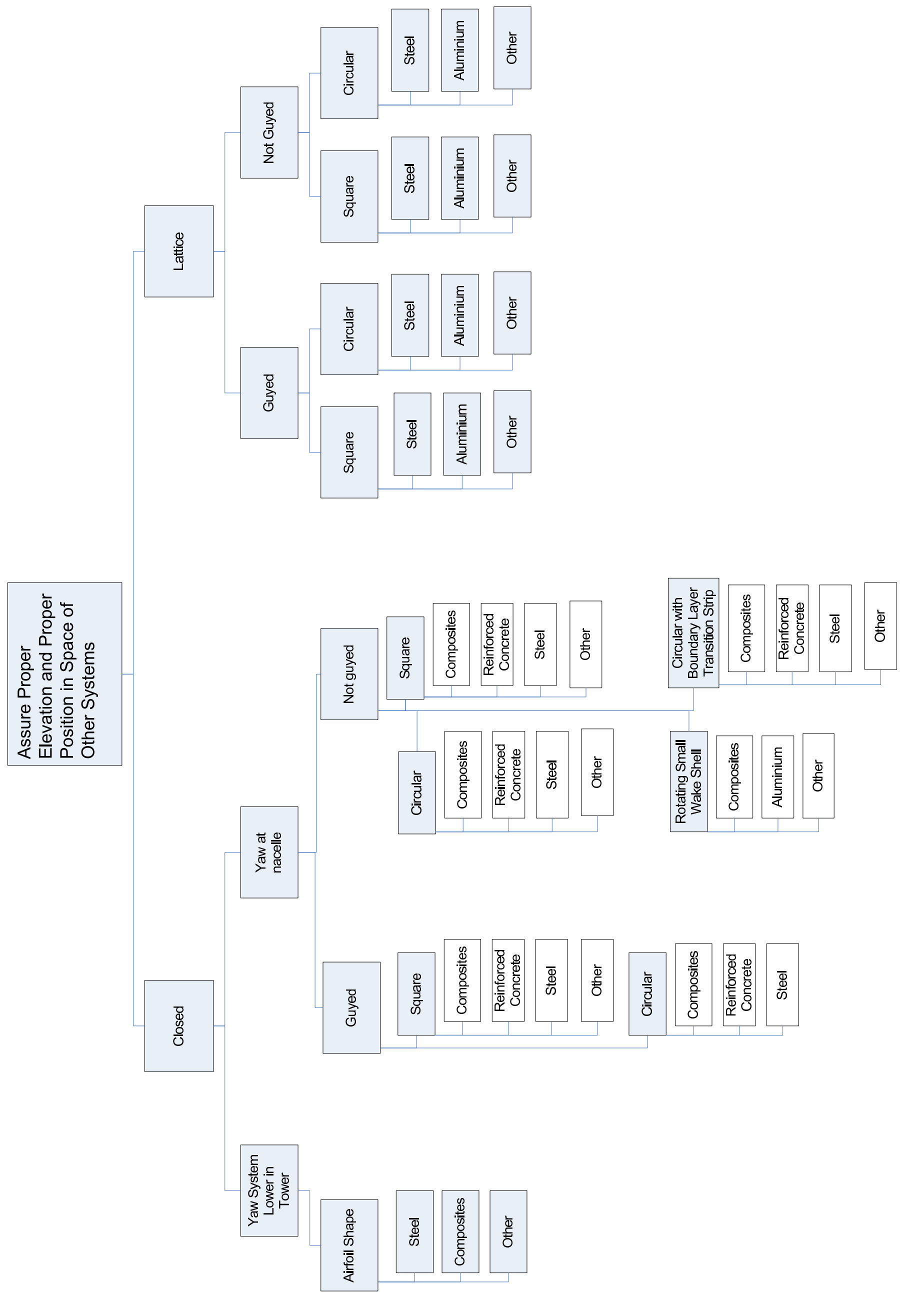

Figure D-1: Design Option Tree of the Tower

D-2 Design Option Tree of the Nacelle

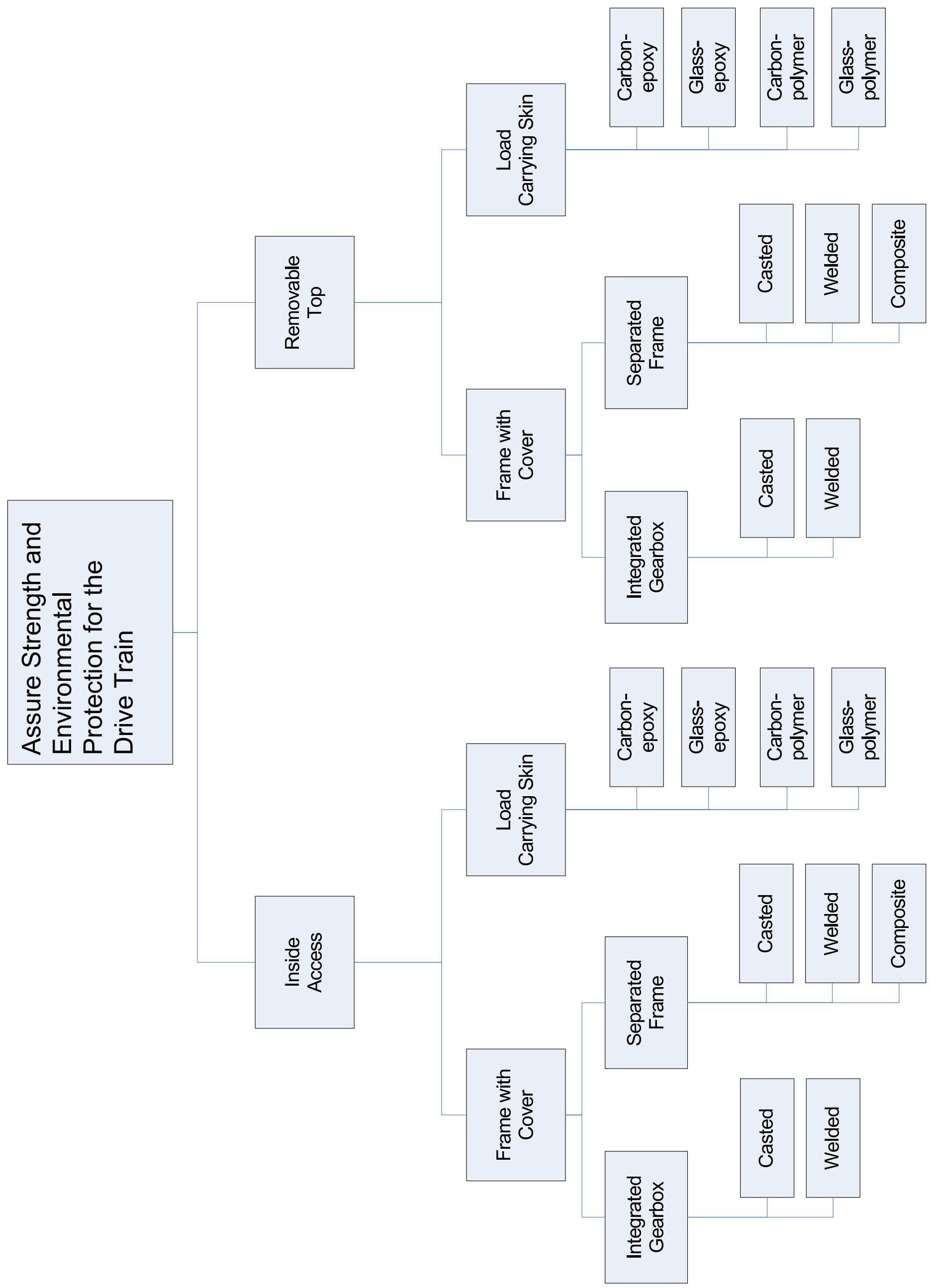

Figure D-2: Design Option Tree of the Nacelle

D-3 Design Option Tree of the Foundation

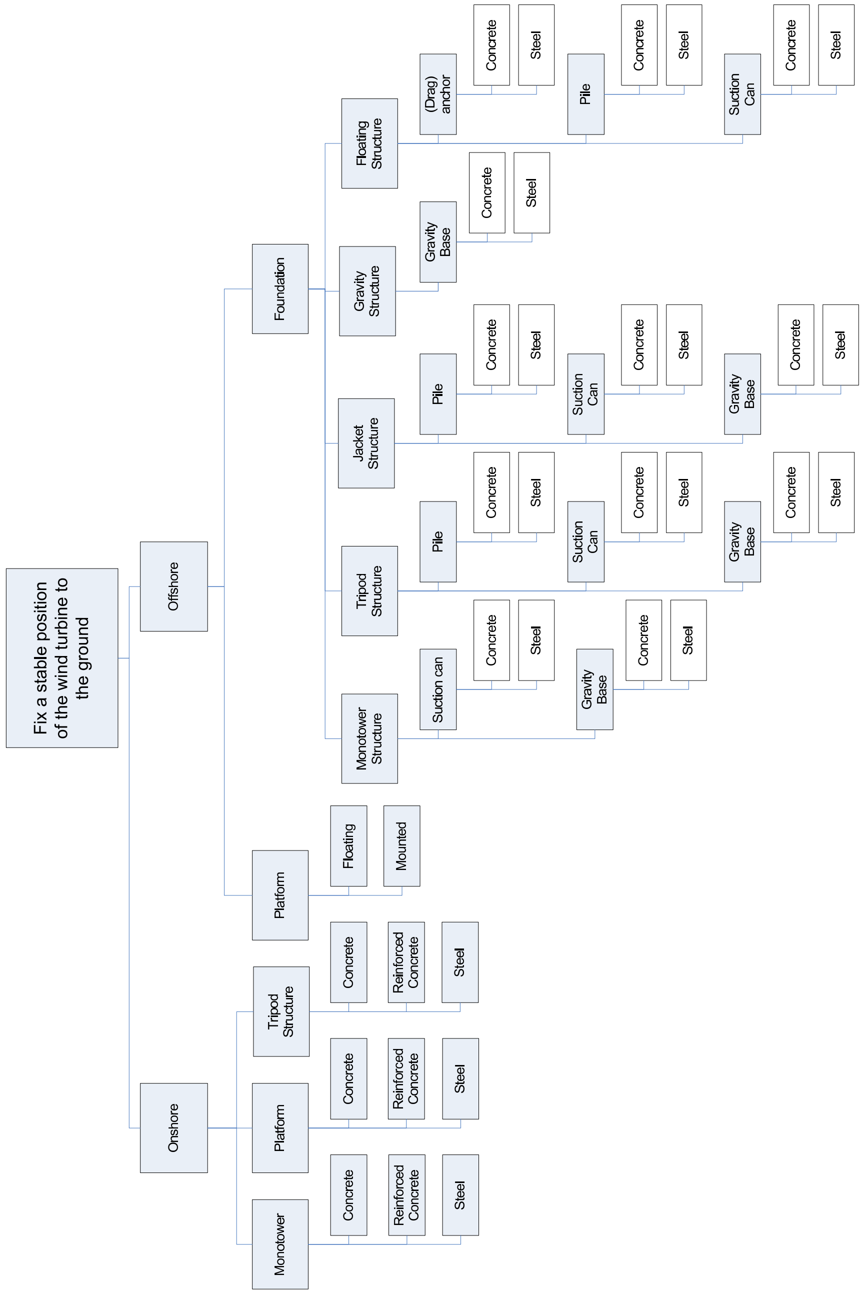

Figure D-3: Design Option Tree of the Foundation

D-4 Design Option Tree of the Control System, part 1

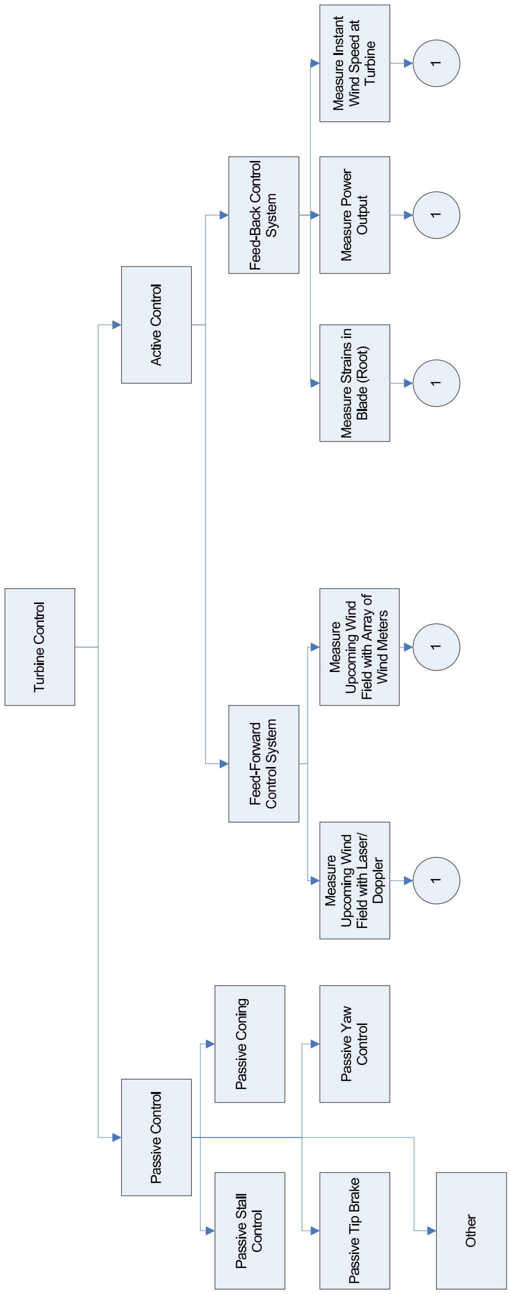

Figure D-4: Design Option Tree of the Control System, part 1

D-5 Design Option Tree of the Control System, part 2

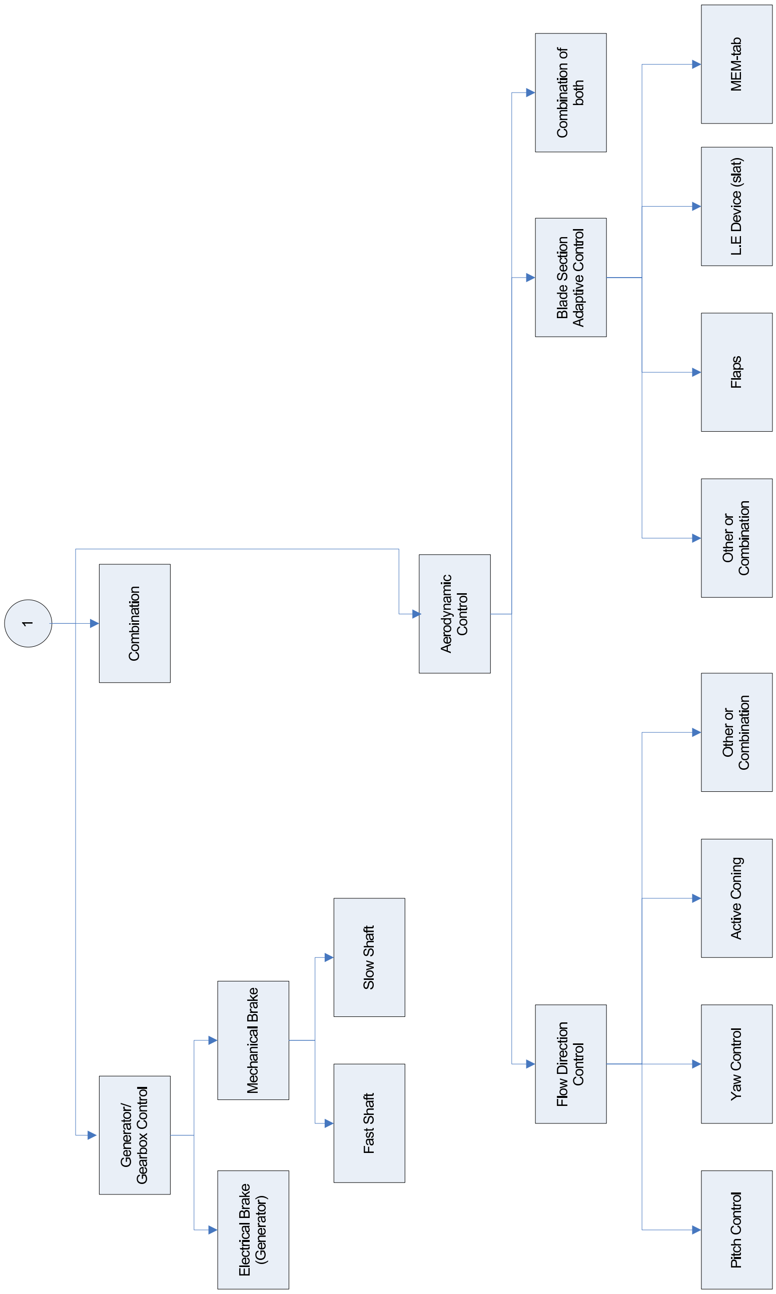

Figure D-5: Design Option Tree of the Control System, part 2

D-6 Design Option Tree of the Rotor, part 1

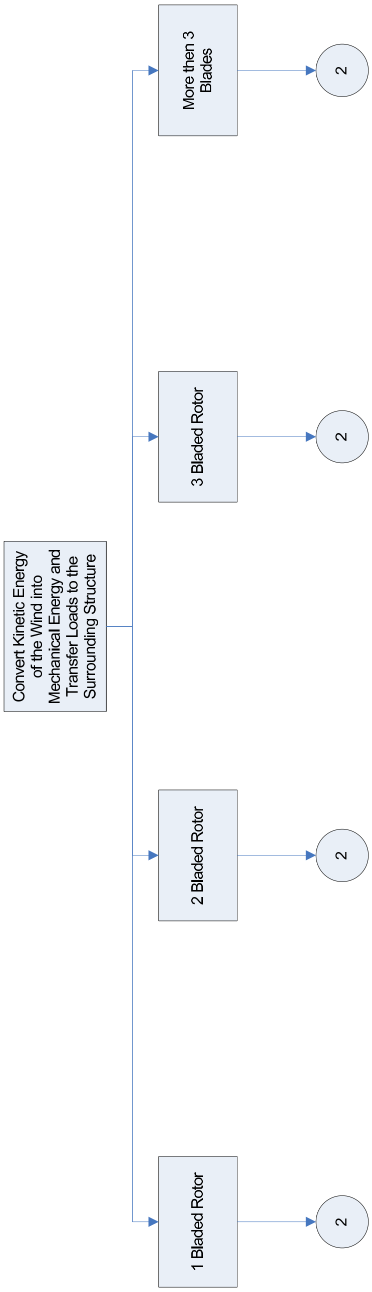

Figure D-6: Design Option Tree of the Rotor, part 1

D-7 Design Option Tree of the Rotor, part 2

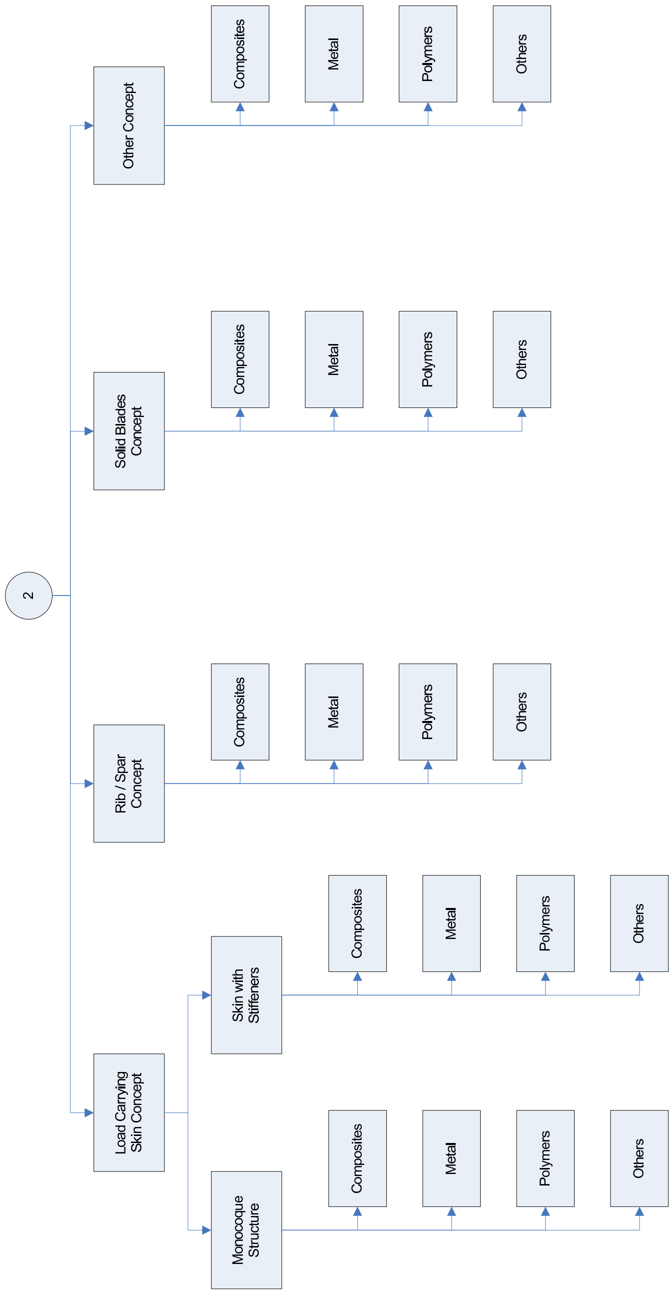

Figure D-7: Design Option Tree of the Rotor, part 2