Great expectations for offshore wind turbines

Emulation of wind farm design to anticipate their value for customers

Michiel Zaaijer
Great expectations for offshore wind turbines

Emulation of wind farm design to anticipate their value for customers

Proefschrift

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Great expectations for offshore wind turbines

Emulation of wind farm design to anticipate their value for customers

To date, the technical feasibility of making electricity from offshore wind energy has been convincingly proven. However, there is a need for improvement in various areas. One of these areas is the cost of energy, because the implementation of offshore wind farms is currently financially dependent of public support schemes. Although it is justified to expect large cost reductions for this relatively young technology, there are several challenges in finding the right solutions. Two of these challenges are addressed in this research. The first challenge is the difficulty of optimisation, due to the multidisciplinary and multi-component nature of offshore wind farms. The second challenge is that the design of the rotor-nacelle assemblies is not performed at the same time as the design of the wind farms in which they are applied. This is the consequence of designing rotor-nacelle assemblies for many wind farms, while most of the rest of the design of the wind farm is site specific. The asynchrony between the design processes hampers collaboration. This makes it difficult to optimise the rotor-nacelle assembly with respect to the cost of energy, because the rotor-nacelle assembly has a large effect on the design of the wind farm. When this effect is not known during the design of the rotor-nacelle assembly, the cost of energy cannot be assessed accurately. The objective of this research is to obtain a method to support the optimisation of rotor-nacelle assemblies that will be applied in offshore wind farms.

To establish a theoretical basis for the method, an abstract version of the problem is formulated. Analysis of the differences between collaborative design and non-collaborative developments is used to formulate the principles of the method and to establish guidelines for the implementation of its instruments. The primary instrument of the method is a software tool that emulates the design processes that are outside the scope of collaboration, but that affect the value of the system for which a sub component is designed. This emulation provides the means to assess the effect of subsystem design variation on the design of other parts of the system and consequentially on its value. The guidelines are applied to test the method for the optimisation of rotor-nacelle assemblies. To this end, a tool is developed that emulates the design of offshore wind farms, based on specifications of the rotor-nacelle assembly. Four use cases are formulated as examples of how designers can use the tool. By variation of specifications of the rotor-nacelle assembly, the designer can assess the effect on the wind farm design and on the cost of energy. The designer can also specify the market for which the rotor-nacelle assembly is optimised, by adjusting the site conditions and number of turbines in the wind farm.

The quality of the emulation of offshore wind farm design is appraised by comparison of emulated designs with realised designs and by analysis of the response to changes in input parameters. The accuracy of the engineering and economic results of the emulation is found to be sufficient to support optimisation of main parameters of the rotor-nacelle assembly. Absolute accuracy of cost of energy is in the order of 20%. More importantly, the response of cost of energy to changes in main parameters of the
rotor-nacelle assembly is clear and in agreement with expectations. Much of the inaccuracy in the absolute value of the levelised production costs drops out in comparative studies of different rotor-nacelle assembly designs.

The usefulness of the method is validated by giving an informed argument, performing a controlled experiment with the tool and by holding a review of the tool by several companies. Each validation supports the utility for the optimisation of the rotor-nacelle assemblies. Several main parameters of the rotor-nacelle are shown to have a clear effect on the cost of energy. The magnitude of this effect and thus of the contribution of the tool to the optimisation is in the order of a few percent. The emulation proves sensitive to many parameters of the rotor-nacelle assembly and of the targeted market. The use of engineering principles helps to identify the origin of benefits and drawbacks and provides additional information to judge validity of the results. Employees of the companies that have tested the emulation tool confirm the utility of the method. However, for the emulation that is implemented in this project several imperfections are identified, such as discontinuous or erratic response of some design variables and the limited control of the user over processes in the tool.

Future prospects of the tool are assessed by comparison with other academic software developments and by analysis of the responses of the reviewers. Wind energy consultants are considered to be in the best position for further developments of the emulation tool. However, engineering software developers can contribute with their expertise in engineering design optimisation. Furthermore, project developers and companies with experience in turn key projects can provide domain specific knowledge for offshore wind farm design. Wind turbine companies should remain involved in the process of continued development, as users of the tool. Introduction of the method is expected to require a change in mindset and organisation for the wind turbine manufacturers. The method addresses system-level design choices that were previously outside the scope of the engineering departments. At the same time, it introduces more engineering than previously used in the strategic decisions of a new product development. Furthermore, users need to become comfortable with working with a tool that works in a domain in which they are no experts.

Experience with the application of the guidelines from the theoretical basis proves that these are relevant and helpful. Other findings of the study with the wind farm emulation tool are held next to literature on design to generalise the results and to assess the practical value of the theoretical basis for other implementations. The separation between the abstract formulations of the theory and the practical implementation is considerable and it is desirable to fill this gap with additional guidelines that indicate which directions of development are expected to lead to success and which don’t. A preliminary assessment of feasibility and potential utility reveals that these two aspects are conflicting. Applications where the method would be most useful involve design processes that are complex to emulate.
De technische haalbaarheid om electriciteit te maken van wind op zee is heden ten dage overtuigend aangetoond. Op verschillende aspecten is echter verbetering nodig. Eén van die aspecten is de energiekosten, omdat op dit moment de bouw van windparken op zee afhankelijk is van ondersteuning door publieke middelen. Hoewel het terecht is om grote kostenreducties te verwachten voor deze jonge technologie ligt er een aantal uitdagingen voor het vinden van de juiste oplossingen. Twee van deze uitdagingen worden in dit onderzoek opgepakt. De eerste uitdaging is de moeilijkheid om de oplossing te optimaliseren, omdat windparken op zee van nature multidisciplinair zijn en uit vele componenten bestaan. De tweede uitdaging is dat het ontwerp van de windturbine niet op hetzelfde moment plaatsvindt als het ontwerp van de windparken waarin ze worden toegepast. Dit is de consequentie van het ontwerpen van windturbines voor gebruik in meerdere windparken, terwijl de meeste andere onderdelen van het windpark specifiek worden ontworpen voor een bepaalde locatie. De asynchroniteit van de ontwerpprocessen zit samenwerking in de weg. Dit maakt het moeilijk om de windturbine te optimaliseren naar de energiekosten, omdat de windturbine een groot effect heeft op het ontwerp van het windpark. Als dit effect niet bekend is tijdens het ontwerp van de windturbine, dan kunnen de energiekosten niet goed geschat worden. Het doel van dit onderzoek is om een methode te verkrijgen die helpt om windturbines te optimaliseren voor gebruik in windparken op zee.

Om een theorethische basis te bewerkstelligen voor de methode is een abstracte versie van de probleemstelling geformuleerd. Een analyse van de verschillen tussen ontwerpprocessen met en zonder samenwerking is gebruikt om principes te formuleren voor de methode en om richtlijnen op te stellen voor de realisatie van instrumenten. Het voornaamste instrument is een computerprogramma dat de ontwerpprocessen nabootst die buiten het bereik van samenwerking vallen, maar die wel invloed hebben op de waarde van het systeem waarvoor het onderdeel wordt ontworpen. Deze nabootsing verschafte de mogelijkheid om het effect te schatten van veranderingen in het ontwerp van het onderdeel op het ontwerp van andere onderdelen en dus op de waarde van het systeem. De richtlijnen zijn toegepast om de methode te testen voor de optimalisatie van windturbines. Hiervoor is een programma ontwikkeld dat het ontwerp van windparken op zee nabootst, al naar gelang de specificatie van de windturbine. Vier methodes van gebruik van het programma door de ontwerper zijn opgesteld als voorbeelden. Door variatie van de specificaties van de windturbine kan de ontwerper het effect op het ontwerp van het windpark en op de energiekosten inschatten. De ontwerper kan ook specificeren voor welke markt de windturbine wordt geoptimaliseerd, door de omgevingscondities en het aantal turbines in het park aan te passen.

De kwaliteit van het nabootsen van het ontwerp van windparken op zee is beoordeeld door nagebootste ontwerpen te vergelijken met gerealiseerde windparken en door de responsie op veranderde input te analyseren. De nauwkeurigheid van technische en economische resultaten is voldoende bevonden om de optimalisatie van belangrijke

Samenvatting

Goede vooruitzichten voor windturbines op zee
Emulatie van windpark-ontwerp om hun waarde voor afnemers te anticiperen

De technische haalbaarheid om electriciteit te maken van wind op zee is heden ten dage overtuigend aangetoond. Op verschillende aspecten is echter verbetering nodig. Eén van die aspecten is de energiekosten, omdat op dit moment de bouw van windparken op zee afhankelijk is van ondersteuning door publieke middelen. Hoewel het terecht is om grote kostenreducties te verwachten voor deze jonge technologie ligt er een aantal uitdagingen voor het vinden van de juiste oplossingen. Twee van deze uitdagingen worden in dit onderzoek opgepakt. De eerste uitdaging is de moeilijkheid om de oplossing te optimaliseren, omdat windparken op zee van nature multidisciplinair zijn en uit vele componenten bestaan. De tweede uitdaging is dat het ontwerp van de windturbine niet op hetzelfde moment plaatsvindt als het ontwerp van de windparken waarin ze worden toegepast. Dit is de consequentie van het ontwerpen van windturbines voor gebruik in meerdere windparken, terwijl de meeste andere onderdelen van het windpark specifiek worden ontworpen voor een bepaalde locatie. De asynchroniteit van de ontwerpprocessen zit samenwerking in de weg. Dit maakt het moeilijk om de windturbine te optimaliseren naar de energiekosten, omdat de windturbine een groot effect heeft op het ontwerp van het windpark. Als dit effect niet bekend is tijdens het ontwerp van de windturbine, dan kunnen de energiekosten niet goed geschat worden. Het doel van dit onderzoek is om een methode te verkrijgen die helpt om windturbines te optimaliseren voor gebruik in windparken op zee.
parameters van de windturbine te ondersteunen. De absolute nauwkeurigheid is ongeveer 20%. Belangrijker is het dat de responsie van de energiekosten op veranderingen in de belangrijke parameters van de windturbine duidelijk is en in overeenstemming is met de verwachtingen. Veel van de onnauwkeurigheid in de absolute waarde van de energiekosten valt weg in een vergelijkende studie van verschillende windturbines.

Het nut van de methode is getoetst door deze te beargumenteren, door een experiment uit te voeren met het programma en door het programma te laten testen door enkele bedrijven. Elk van deze toetsen beamt het nut voor de optimalisatie van windturbines. Voor diverse belangrijke parameters van de windturbine wordt getoond dat deze een duidelijk effect hebben op de energiekosten. De grootte van dit effect, en dus van de bijdrage van het programma aan de optimalisatie, is enkele procenten. Het nabootsen van het windparkontwerp is gevoelig voor verandering in veel parameters van de windturbine en parameters die de beoogde markt specificeren. Het gebruik van engineering principes helpt om de oorsprong van voor- en nadelen te identificeren en geeft extra informatie om de juistheid van de resultaten te beoordelen. Medewerkers van de bedrijven die het programma hebben getest bevestigen het nut van de methode. Voor de implementatie van het programma is echter wel een aantal tekortkomingen geconstateerd, zoals discontinue of onregelmatige responsie van enkele onterwepparameters en de beperkte invloed van de gebruiker op processen in het programma.


Ervaring met de toepassing van de richtlijnen die de theoretische basis verschafte laat zien dat deze relevant en behulpzaam zijn. Andere bevindingen van de studie met het programma voor windparken zijn naast literatuur over ontwerpen gehouden om de resultaten te generaliseren en om de praktische waarde van de theoretische basis in te schatten. De afstand tussen de abstracte formulering van de theorie en de praktische implementatie is groot en het is wenselijk om dit gat te vullen met aanvullende richtlijnen die aangeven welke ontwikkelingen leiden naar succes. Een inschatting van de haalbaarheid en bruikbaarheid laat zien dat deze twee aspecten tegenpolen zijn. Toepassingen waar de methode het meeste kan opleveren brengen processen met zich mee die lastig zijn na te bootsen.
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The tool that was developed for this research has been tested by several engineers. I want to thank employees of GE Energy, GL Garrad Hassan, Siemens Wind Power, Vestas Wind Systems, XEMC-Darwind and 2-B Energy for their willingness to listen to my ideas. Particularly, I want to thank the engineers of these companies that eventually performed the tests, Henk-Jan Kooijman, Wouter Haans, Christiaan Torres Stöckl, Dick Veldkamp and Vipul Gupta. The unconditional effort of these people has made the project so much more useful, as I strongly believe the utility of a design method cannot be judged properly without the judgement of people in the field.

I like to express my great appreciation for the members of the doctoral committee. Without exception, they immediately showed their interest in my work and their willingness to accept the demanding task of taking the opposition. Even before the defence I received valuable feedback, useful for my preparation and, more importantly, for my future work.

During the execution of the project I have been advised and coached by my supervisors, Gijs van Kuik, Gerard van Bussel and Michel van Tooren. Their feedback and our discussions are gratefully acknowledged. Throughout the work they have kept me sharp, forced me to communicate effectively and always showed how there are different ways of looking at the same thing. Only for the rule ‘three is a crowd’ could Michel eventually not formally be recorded as promotor.

Besides these direct contributions to my research, I have been greatly supported and influenced by the people around me. During their project work many students have helped me in forming and articulating my ideas. I also want to thank my colleagues, inside our research group, inside the university and outside the university. The many talks I had with them gave me much information that helped me with my research and with putting it in a wider context. Furthermore, I received much practical help that underlines the essence of collegiality. Relating to my work, my family and friends helped me put my research in a societal perspective, with their inquisitive questions. However, the greatest contribution of my family and friends has been their ability to sometimes make me completely forget the sorrows of doing PhD research!
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## List of symbols

### Latin symbols

<table>
<thead>
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<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$A$</td>
<td>state matrix of parameter dependencies</td>
</tr>
<tr>
<td>$A$</td>
<td>parameter dependency matrix for self-affecting process</td>
</tr>
<tr>
<td>$A_c$</td>
<td>cross-sectional area of conductor</td>
</tr>
<tr>
<td>$A_{farm}$</td>
<td>area occupied by wind farm</td>
</tr>
<tr>
<td>$A_{wake}$</td>
<td>area of incidence of partial wake or multiple wake overlap</td>
</tr>
<tr>
<td>$A_{KC}$</td>
<td>amplification of wave water particle velocity</td>
</tr>
<tr>
<td>$A_m$</td>
<td>state matrix of parameter dependencies for domain of the mind</td>
</tr>
<tr>
<td>$A_r$</td>
<td>state matrix of parameter dependencies for domain of reality</td>
</tr>
<tr>
<td>$A_{am}$</td>
<td>parameter dependency matrix for self-affecting process in the mind</td>
</tr>
<tr>
<td>$A_{ar}$</td>
<td>parameter dependency matrix for self-affecting process in reality</td>
</tr>
<tr>
<td>$a$</td>
<td>constant in polynomial</td>
</tr>
<tr>
<td>$B$</td>
<td>input matrix of parameter dependencies</td>
</tr>
<tr>
<td>$B$</td>
<td>cross-domain parameter dependency matrix</td>
</tr>
<tr>
<td>$B'$</td>
<td>cross-domain dependency matrix that is new for collaborative design</td>
</tr>
<tr>
<td>$B_m$</td>
<td>input matrix of parameter dependencies for domain of the mind</td>
</tr>
<tr>
<td>$B_r$</td>
<td>input matrix of parameter dependencies for domain of reality</td>
</tr>
<tr>
<td>$B_m'$</td>
<td>cross-domain parameter dependency matrix from mind to reality</td>
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<tr>
<td>$B_r'$</td>
<td>cross-domain parameter dependency matrix from reality to mind</td>
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<tr>
<td>$b$</td>
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</tr>
<tr>
<td>$b$</td>
<td>exponent of storm fraction function</td>
</tr>
<tr>
<td>$b$</td>
<td>exponent of storm length function</td>
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<tr>
<td>$C$</td>
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</tr>
<tr>
<td>$C'$</td>
<td>capacitance of electrical cable per unit length</td>
</tr>
<tr>
<td>$C_{bl}$</td>
<td>actualised total bottom lease costs</td>
</tr>
<tr>
<td>$C_{capital}$</td>
<td>capital costs excluding management costs</td>
</tr>
<tr>
<td>$C_{decommissioning}$</td>
<td>decommissioning costs excluding management costs</td>
</tr>
<tr>
<td>$C_{foundation installation}$</td>
<td>costs of foundation installation</td>
</tr>
<tr>
<td>$C_{infield}$</td>
<td>actualised total infield cable costs</td>
</tr>
<tr>
<td>$C_m$</td>
<td>output matrix of parameter dependencies for domain of the mind</td>
</tr>
<tr>
<td>$C_{O&amp;M}$</td>
<td>costs of operation and maintenance excluding management costs</td>
</tr>
<tr>
<td>$C_{offshore works}$</td>
<td>costs of offshore works of rotor-nacelle assembly installation</td>
</tr>
<tr>
<td>$C_{PM}$</td>
<td>costs of consumables per maintenance visit</td>
</tr>
</tbody>
</table>
\( C_{RNA} \) costs of rotor-nacelle assembly
\( C_{RNA,new} \) costs of new rotor-nacelle assembly design
\( C_{RNA,ref} \) costs of reference rotor-nacelle assembly design V80
\( C_r \) output matrix of parameter dependencies for domain of reality
\( C_{repair,j} \) costs of consumables per repair of failure type \( j \)
\( C_{rest} \) actualised costs without bottom lease and infield cable costs
\( C_t \) costs for year \( t \)
\( C_{t,i} \) costs for year \( t \) for wind farm \( i \)
\( C_{vessel} \) costs of access vessel rental
\( c \) constant in polynomial
\( c \) Weibull scale factor
\( c_d \) drag coefficient
\( c_m \) inertia coefficient
\( c_r \) thrust coefficient
\( c_{r,\text{storm}} \) Weibull scale factor for storm length
\( c_{r,\text{storm,ref}} \) Weibull scale factor for storm length for reference access method
\( D \) diameter
\( D \) feedthrough matrix of parameter dependencies
\( D_\alpha \) dimensionless grain size
\( D_a \) diameter of the armour
\( D_{\text{base}} \) diameter at the base
\( D_{bi} \) diameter of the binder
\( D_c \) diameter of the conductor
\( D_{cs} \) diameter of the conductor screen
\( D_i \) diameter of the insulation
\( D_{is} \) diameter of the insulation screen
\( D_m \) feedthrough matrix of parameter dependencies for domain of the mind
\( D_{os} \) diameter of outer serving
\( D_{\text{pile}} \) outer diameter of monopile
\( D_r \) feedthrough matrix of parameter dependencies for domain of reality
\( D_{\text{rotor}} \) rotor diameter
\( D_{\text{rotor,new}} \) rotor diameter of new rotor-nacelle assembly design
\( D_{\text{rotor,ref}} \) rotor diameter of reference rotor-nacelle assembly design V80
\( D_{\text{top}} \) diameter at the top
\( D_{\text{tower}} \) outer diameter of tower
\( d \) distance between centres of wake and rotor or of two wakes
\( d_{15} \) 15 percentile sieve size of rock
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$d_{15, \text{armour}}$</td>
<td>15 percentile sieve size of rock in armour layer</td>
</tr>
<tr>
<td>$d_{15, \text{base}}$</td>
<td>15 percentile sieve size of rock or soil below filter layer</td>
</tr>
<tr>
<td>$d_{15, \text{filter}}$</td>
<td>15 percentile sieve size of rock in filter layer</td>
</tr>
<tr>
<td>$d_{50}$</td>
<td>50 percentile sieve size of soil or rock</td>
</tr>
<tr>
<td>$d_{50, \text{base}}$</td>
<td>50 percentile sieve size of rock or soil below filter layer</td>
</tr>
<tr>
<td>$d_{50, \text{filter}}$</td>
<td>50 percentile sieve size of rock in filter layer</td>
</tr>
<tr>
<td>$d_{85}$</td>
<td>85 percentile sieve size of rock</td>
</tr>
<tr>
<td>$d_{85, \text{base}}$</td>
<td>85 percentile sieve size of rock or soil below filter layer</td>
</tr>
<tr>
<td>$d_{85, \text{filter}}$</td>
<td>85 percentile sieve size of rock in filter layer</td>
</tr>
<tr>
<td>$d_{85, \text{filter}_i}$</td>
<td>85 percentile sieve size of rock in filter layer $i$</td>
</tr>
<tr>
<td>$d_{90}$</td>
<td>90 percentile sieve size of soil</td>
</tr>
<tr>
<td>$d_{\text{burial}}$</td>
<td>burial depth</td>
</tr>
<tr>
<td>$d_{\text{clamping}}$</td>
<td>pile clamping depth below mudline</td>
</tr>
<tr>
<td>$d_{\text{ecc}}$</td>
<td>eccentricity of centre of gravity</td>
</tr>
<tr>
<td>$d_h$</td>
<td>distance from harbour to boundary of wind farm</td>
</tr>
<tr>
<td>$d_{n50}$</td>
<td>50% passing nominal diameter</td>
</tr>
<tr>
<td>$d_{\text{water}}$</td>
<td>water depth</td>
</tr>
<tr>
<td>$E$</td>
<td>electricity production</td>
</tr>
<tr>
<td>$E_d$</td>
<td>design modulus of elasticity</td>
</tr>
<tr>
<td>$E_{\text{loss, e}}$</td>
<td>annual loss in electrical infrastructure</td>
</tr>
<tr>
<td>$E'_s$</td>
<td>actualised total energy yield without electrical and array losses</td>
</tr>
<tr>
<td>$E_i$</td>
<td>annual electricity production</td>
</tr>
<tr>
<td>$E_t$</td>
<td>electricity production in year $t$</td>
</tr>
<tr>
<td>$E_{t,i}$</td>
<td>electricity production in year $t$ for wind farm $i$</td>
</tr>
<tr>
<td>$E_{t,j}$</td>
<td>electricity production in year $t'$ for wind farm $j$</td>
</tr>
<tr>
<td>$e$</td>
<td>equivalent geometrical imperfection</td>
</tr>
<tr>
<td>$F_d$</td>
<td>drag force</td>
</tr>
<tr>
<td>$F_{d}$</td>
<td>amplitude of drag force</td>
</tr>
<tr>
<td>$F_g$</td>
<td>gravity force</td>
</tr>
<tr>
<td>$F_{i}$</td>
<td>amplitude of inertia force</td>
</tr>
<tr>
<td>$F_{\text{lat}}$</td>
<td>lateral force on pile at mudline</td>
</tr>
<tr>
<td>$F_z$</td>
<td>force in $z$ direction</td>
</tr>
<tr>
<td>$f$</td>
<td>frequency of alternating current</td>
</tr>
<tr>
<td>$f_s$</td>
<td>storm fraction</td>
</tr>
<tr>
<td>$f_{s, \text{ref}}$</td>
<td>storm fraction for reference access method</td>
</tr>
<tr>
<td>$f_w$</td>
<td>wave friction factor</td>
</tr>
<tr>
<td>$f_{\text{warranty}}$</td>
<td>warranty percentage of rotor-nacelle assembly costs</td>
</tr>
</tbody>
</table>
\( f_{wr} \) rough bed friction factor
\( f_{ws} \) smooth bed friction factor
\( f_{yd} \) design yield stress
\( f \) objective function
\( f \) probability density function
\( f \) state function
\( f_\varphi \) probability density function in wind direction \( \varphi \)
\( f_{\text{fixed}} \) fraction of costs that remain the same during scaling of mass
\( f_{\text{shift length}} \) factor on wage for shift length
\( f_{\text{shift rotation}} \) factor on wage for number of shifts per day
\( G \) geometrical factor
\( g \) gravity constant
\( g \) output function
\( g_e \) inequality constraint function vector of external design processes
\( g_i \) inequality constraint function vector of internal design processes
\( g_j \) inequality constraint function vector of discipline \( j \)
\( H \) total height of structure
\( H \) wave height
\( H_b \) braking wave height
\( H_s \) significant wave height
\( H_{s,\text{ref}} \) significant wave height for accessibility with reference access method
\( h \) height
\( h_e \) equality constraint function vector of external design processes
\( h_{\text{hub}} \) hub height
\( h_i \) equality constraint function vector of internal design processes
\( h_j \) equality constraint function vector of discipline \( j \)
\( h_j \) hazard rate for failure of type \( j \)
\( h_{\text{ref}} \) reference height
\( I \) moment of inertia
\( I_{\text{active}} \) active current
\( I_{\text{rated}} \) rated current per phase
\( I_{\text{reactive}} \) reactive current
\( I_{\text{reactive,shunt}} \) reactive current in shunt reactor
\( I_{\text{total}} \) total current
\( K \) screening factor
\( K_a \) active pressure coefficient
$K_p$  
passive pressure coefficient

$KC$  
Keulegan-Carpenter number

$k$  
conditional objective function

$k$  
core radius of a tube

$k$  
wake expansion factor

$k$  
wave number

$k$  
Weibull shape factor

$k_{\text{storm}}$  
Weibull shape factor for storm length

$k_s$  
Nikuradse equivalent sand grain roughness

$L$  
inductance

$L$  
transportation distance onshore

$l$  
length of the transmission cable

$l$  
total length of infield cables

$l_{\text{base-to-top}}$  
length of element from base to top

$l_{\text{overlap}}$  
length of overlap between monopile and transition piece

$LPC$  
levelised production costs

$LPC_i$  
levelised production costs of wind farm $i$

$M$  
flapping moment

$M$  
number of disciplines

$M_d$  
moment due to drag force

$\hat{M}_d$  
amplitude of moment due to drag force

$\hat{M}_i$  
amplitude of moment due to inertia force

$M_{\text{rot}}$  
bending moment on pile at mudline

$M_y$  
moment in direction perpendicular to the direction

$MTBF$  
mean time between failures

$MTBF_j$  
mean time between failures for failure of type $j$

$m_{\text{copper}}$  
mass of copper in cable

$m_{\text{grout}}$  
mass of grout

$m_{\text{insulation}}$  
mass of insulation material in cable

$m_{\text{jacket}}$  
mass of jacket of transform platform

$m_{\text{nacelle}}$  
mass of nacelle

$m_{\text{pile}}$  
mass of monopile

$m_{\text{RNA}}$  
mass of rotor-nacelle assembly

$m_{\text{rotor}}$  
mass of rotor

$m_{\text{tower}}$  
mass of tower

$m_{\text{transition piece}}$  
mass of transition piece

$N_{b,i}$  
number of sub-batches of repair batch $i$
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_c$</td>
<td>number of turbines in column</td>
</tr>
<tr>
<td>$N_{crew}$</td>
<td>number of crews per shift</td>
</tr>
<tr>
<td>$N_{cubicle, collection}$</td>
<td>number of switchgear cubicles at infield side of platform</td>
</tr>
<tr>
<td>$N_{cubicle, connection}$</td>
<td>number of switchgear cubicles at grid connection point</td>
</tr>
<tr>
<td>$N_{cubicle, transmission}$</td>
<td>number of switchgear cubicles at transmission side of platform</td>
</tr>
<tr>
<td>$N_{cubicle, turbines}$</td>
<td>number of switchgear cubicles in turbines</td>
</tr>
<tr>
<td>$N_{el}$</td>
<td>Euler force for cantilever beam according to theory of elasticity</td>
</tr>
<tr>
<td>$N_{f,i,j}$</td>
<td>number of failures of type $j$ during repair batch $i$</td>
</tr>
<tr>
<td>$N_{f,s,j}$</td>
<td>number of failures of type $j$, after storm</td>
</tr>
<tr>
<td>$N_{f,s+cu,j}$</td>
<td>number of failures of type $j$ during storm and catch-up period</td>
</tr>
<tr>
<td>$N_{f,ss,j}$</td>
<td>number of failures of type $j$ during steady state</td>
</tr>
<tr>
<td>$N_{f,total,j}$</td>
<td>number of failures of type $j$</td>
</tr>
<tr>
<td>$N_{f,total,lift}$</td>
<td>number of failures that require lifting equipment</td>
</tr>
<tr>
<td>$N_{mob}$</td>
<td>number of mobilisations of lifting equipment per year</td>
</tr>
<tr>
<td>$N_{n}$</td>
<td>number of mobilisations of lifting equipment for $n$ repairs</td>
</tr>
<tr>
<td>$N_{p}$</td>
<td>number of people per crew</td>
</tr>
<tr>
<td>$N_{passengers}$</td>
<td>number of passengers per vessel</td>
</tr>
<tr>
<td>$N_{pm}$</td>
<td>number of preventive maintenance actions</td>
</tr>
<tr>
<td>$N_{r}$</td>
<td>number of turbines in row</td>
</tr>
<tr>
<td>$N_{s}$</td>
<td>number of shifts per day</td>
</tr>
<tr>
<td>$N_{storms}$</td>
<td>number of storms during lifetime of wind farm</td>
</tr>
<tr>
<td>$N_{t}$</td>
<td>number of turbines in farm</td>
</tr>
<tr>
<td>$N_{t,branch}$</td>
<td>number of turbines in branch upstream of the position in the cable</td>
</tr>
<tr>
<td>$N_{t,d,i,j}$</td>
<td>number of turbines with failures of type $j$ at start of repair batch $i$</td>
</tr>
<tr>
<td>$N_{t,ss}$</td>
<td>number of operational turbines during the steady state</td>
</tr>
<tr>
<td>$N_{vessels}$</td>
<td>number of vessels</td>
</tr>
<tr>
<td>$N_{wakes}$</td>
<td>number of wakes</td>
</tr>
<tr>
<td>$n$</td>
<td>number of individuals</td>
</tr>
<tr>
<td>$n_L$</td>
<td>number of lines</td>
</tr>
<tr>
<td>$P$</td>
<td>power</td>
</tr>
<tr>
<td>$P_{\text{farm, rated}}$</td>
<td>power rating of wind farm</td>
</tr>
<tr>
<td>$P_i$</td>
<td>power rating of turbine $i$</td>
</tr>
<tr>
<td>$P_{\text{loss, e, full-load}}$</td>
<td>loaded power loss in electrical infrastructure at rated power</td>
</tr>
<tr>
<td>$P_{\text{loss, e, no-load}}$</td>
<td>no-loaded power loss in electrical infrastructure</td>
</tr>
<tr>
<td>$P_{\text{loss, shunt}}$</td>
<td>power loss in shunt reactor</td>
</tr>
<tr>
<td>$P_{\text{loss, t, full-load}}$</td>
<td>loaded power loss in transformer at rated power</td>
</tr>
<tr>
<td>$P_{\text{loss, t, no-load}}$</td>
<td>no-loaded power loss in transformer</td>
</tr>
</tbody>
</table>
$P_{\text{shunt}}$ power rating of shunt reactor
$P_{\text{shunt, offshore}}$ power rating of offshore shunt reactor
$P_{\text{shunt, onshore}}$ power rating of onshore shunt reactor
$P_{\text{trafo, rated}}$ power rating of transformer
$P_{\text{turbine}}$ power of turbine
$P_{\text{turbine, rated}}$ power rating of turbine
$p_d$ probability of being down and on the waiting list during steady state
$p_{\text{mob, n}}$ probability of mobilising hoisting equipment for $n$ repairs
$R$ radius of wake or rotor
$R'$ resistance per unit length
$R_{\theta}$ resistance per unit length at $20^\circ$
$R_g$ resistance per unit length excluding sheath and armour loss
$R_i$ revenues for year $t$ (outside sales of electricity)
$R_{i,j}$ revenues for year $t$ (outside sales of electricity) for wind farm $i$
$R_w$ wave Reynolds number
$r$ real interest rate
$r$ radius of wake
$r_j$ target function for discipline $j$
$r_{\text{offshore}}$ winding ratio of offshore transformer
$r_{\text{onshore}}$ winding ratio of onshore transformer
$r_r$ relative roughness
$r_{\text{turbine}}$ winding ratio of turbine transformer
$s_c$ spacing between turbines in column
$s_r$ spacing between turbines in row
$T$ wave period
$T'$ duration of period covering the lifetime of multiple wind farms
$T_1$ thermal resistance between conductor and sheath
$T_2$ thermal resistance between sheath and armour
$T_3$ thermal resistance of outer serving
$T_4$ thermal resistance of soil
$T_{b,i}$ duration of repair batch $i$
$T_{\text{catch up}}$ time of catch-up period
$T_{d,f,i,j}$ downtime of turbines that fail during batch $i$
$T_{d,\text{lift}}$ downtime due to waiting for lifting equipment
$T_{d,\text{lift, n}}$ downtime due to waiting for lifting equipment to do $n$ repairs
$T_{d, \text{pm}}$ downtime during preventive maintenance
$T_{d, \text{prepare, storm, j}}$ downtime due to preparation for type $j$ in storm and catch-up period
$T_{d,prepare,j}$  downtime during preparations for failures of type $j$ in steady state

$T_{d,s,j}$  downtime of failures of type $j$ that happen during a storm

$T_{d,s+cu,j}$  downtime due to failures of type $j$ during storm and catch-up period

$T_{d,total}$  total downtime

$T_{d,total,j}$  total downtime assigned to failures of type $j$

$T_{d,w,i,j}$  downtime of previously failed turbines during batch $i$

$T_{d,wait}$  downtime due to waiting list in steady state

$T_{d,wip,j}$  downtime during work in progress for failures of type $j$ in steady state

$T_{day}$  time in a day

$T_{diagnose,j}$  time to perform diagnosis of failure of type $j$

$T_{fix,j}$  time to perform repair activity for failure of type $j$

$T_{life}$  (economic) lifetime of wind farm

$T_{life,i}$  (economic) lifetime of wind farm $i$

$T_{lift}$  total time that lifting equipment is in the wind farm per year

$T_{m}$  time needed for mobilising lifting equipment

$T_{mc}$  waiting time before ordering lifting equipment

$T_{new}$  thrust of new rotor-nacelle assembly design

$T_{pd,j}$  time to process diagnosis information of failure of type $j$

$T_{pm}$  working hours per preventive maintenance action

$T_{pm,total}$  work in progress time of all preventive maintenance actions

$T_{prepare,j}$  downtime during preparations for failures of type $j$

$T_{ref}$  thrust of reference rotor-nacelle assembly design V80

$T_{shift}$  shift duration

$T_{si}$  average interval in which service is required per turbine

$T_{sp,j}$  time for ordering of spare parts of failure of type $j$

$T_{st}$  total steady state time

$T_{storm}$  storm length

$T_{t,in}$  travel time in wind farm

$T_{t,to}$  travel time to and from wind farm

$T_{vessel}$  total time of access vessel rental per year

$T_{wip,j}$  time of work in progress for repair of failure of type $j$

$T_{wip,lift}$  average work in progress time for lifting activities

$T_{wip,pm}$  work in progress time per preventive maintenance action

$t$  target vector

$t$  time

$t$  wall thickness

$t$  year into the lifetime of wind farm

xx
$t'$ year in period covering the lifetime of multiple wind farms
$\tau_{0,i}$ year of start of the lifetime of wind farm
$t_a$ armour thickness
$t_b$ bedding thickness
$t_{b,cu,s}$ time at beginning of catch up of repairs in storm cycle $s$
$t_{b,ss,s}$ time at beginning of storm in storm cycle $s$
$t_{bis}$ binder thickness
$t_{cs}$ conductor screen thickness
$t_{down,i,j,s,k}$ downtime turbine $i$, failure type $j$, storm cycle $s$ and failure $k$
$t_{e,cu,s}$ time at end of catch up of repairs in storm cycle $s$
$t_{e,ss,s}$ time at end of storm in storm cycle $s$
$t_{fail,i,j,k}$ time of failure number $k$ of turbine $i$ with failure type $j$
$t_j$ insulation screen thickness
$t_{is}$ insulation screen thickness
$t_{j}$ target value for discipline $j$
$t_{os}$ outer serving thickness
$t_{pole}$ wall thickness of monopile
$t_{ps}$ polyethylene sheath thickness
$t_{repair,i,j,k}$ time of repair of failure number $k$ of turbine $i$ with failure type $j$
$t_{rest}$ thickness of other cable layers
$t_s$ sheath thickness
$\bar{U}$ depth averaged current velocity
$U_w$ amplitude of seabed orbital velocity
$u$ input vector
$u_{m,i}$ input vector for the mind of person $i$
$u_r$ input vector for the domain of reality
$V$ wind speed
$V_0$ undisturbed wind speed
$V_h$ wind speed at height $h$
$V_i$ wind speed in wake of turbine $i$
$V_L$ line voltage
$V_{L,grid}$ grid line voltage
$V_{L,infield}$ infield line voltage
$V_{L,transmission}$ transmission line voltage
$V_m$ wind speed in mixed wake
$V_{new}$ wind speed for new rotor-nacelle assembly design
$V_{ref}$ wind speed for power curve of rotor-nacelle assembly design $V_{80}$
\( V_{\text{ref}} \) wind speed at reference height
\( V_{\text{scour~protection}} \) volume of scour protection
\( V_r \) speed of vessel
\( V_y \) annual average wind speed
\( W_d \) dielectric cable loss per unit length
\( W_r \) resistive cable loss per unit length
\( W_{\text{total}} \) total cable loss per unit length
\( x \) design vector
\( x \) distance downwind from the rotor
\( x \) position in cable
\( x \) state vector
\( x' \) combined vector of state and output parameters
\( x_e \) design vector of external design processes
\( x_i \) design vector of internal design processes
\( x_j \) design vector of discipline \( j \)
\( x_{m,i} \) state vector of the mind of person \( i \)
\( x'_{m,i} \) combined vector of state and output parameters of mind of person \( i \)
\( x_r \) state vector of the domain of reality
\( x'_{r} \) combined vector of state and output parameters of domain of reality
\( y \) linking variables
\( y \) output vector
\( y_{m,i} \) output vector for the mind of person \( i \)
\( y_r \) output vector for the domain of reality
\( z \) vertical coordinate – positive upwards
\( z_0 \) hydraulic roughness length
\( z_{\text{base}} \) \( z \) - coordinate at the base of an element
\( z_{lo} \) \( z \) - coordinate of low end of integration of force or moment
\( z_{hi} \) \( z \) - coordinate of high end of integration of force or moment
\( z_{\text{ref}} \) \( z \) - coordinate of reference point for moment

**Greek symbols**

\( \alpha \) wind shear exponent
\( \alpha_0 \) temperature coefficient
\( \Delta A \) self-affecting process matrix that differs for collaborative design
\( \Delta B \) cross-domain dependency matrix that differs for collaborative design
\( \Delta \) parameter dependency matrix that differs for collaborative design
\( \delta \) phase angle between charging and capacitive current
\( \varepsilon \)  
reduction factor

\( \varepsilon_0 \)  
dielectric constant in vacuum

\( \varepsilon_a \)  
reduction factor for stress due to axial force

\( \varepsilon_b \)  
reduction factor for stress due to bending moment

\( \varepsilon_{j,i} \)  
fluctuation of efficiency of type \( j \) and turbine \( i \)

\( \varepsilon_r \)  
relative dielectric constant of insulation material

\( \phi \)  
angle between waves and current

\( \varphi \)  
wind direction

\( \gamma' \)  
submerged unit weight

\( \eta_j \)  
time independent efficiency of type \( j \)

\( \eta_{j,i} \)  
time dependent efficiency of type \( j \) and turbine \( i \)

\( \eta_{array,i} \)  
array efficiency of turbine \( i \)

\( \eta_{availability} \)  
average availability fraction of all turbine in wind farm

\( \eta_{availability,i} \)  
availability of turbine \( i \)

\( \eta_{crew} \)  
efficiency of crew deployment

\( \eta_{electrical} \)  
efficiency of electrical network

\( \eta_{shunt} \)  
efficiency of shunt reactor

\( \lambda_1 \)  
sheath loss factor

\( \lambda_2 \)  
armour loss factor

\( \lambda_a \)  
relative slenderness ratio for buckling

\( \lambda_r \)  
relative slenderness ratio for global stability

\( \mu \)  
relative depth of cable burial

\( \nu \)  
Poisson’s ratio

\( \nu_w \)  
kinematic viscosity of water

\( \theta \)  
temperature

\( \theta_{ambient} \)  
ambient temperature

\( \theta_{cr} \)  
critical Shields parameter

\( \theta_{insulation} \)  
maximum temperature in insulation

\( \rho \)  
density

\( \rho_{20} \)  
resistivity at 20°

\( \rho_b \)  
thermal resistivity of bedding

\( \rho_i \)  
thermal resistivity of insulation

\( \rho_{os} \)  
thermal resistivity of outer serving

\( \rho_s \)  
density of soil

\( \rho_s \)  
thermal resistivity of sheath

\( \rho_{soil} \)  
thermal resistivity of soil

\( \rho_w \)  
density of water
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\hat{\zeta}$</td>
<td>amplitude of water elevation</td>
</tr>
<tr>
<td>$\sigma_{axial}$</td>
<td>normal stress due to axial force</td>
</tr>
<tr>
<td>$\sigma_{bending}$</td>
<td>normal stress due to bending moment</td>
</tr>
<tr>
<td>$\sigma_{cr}$</td>
<td>critical compressive stress</td>
</tr>
<tr>
<td>$\sigma_{el}$</td>
<td>critical compressive stress according to theory of elasticity</td>
</tr>
<tr>
<td>$\sigma_{total}$</td>
<td>total normal stress</td>
</tr>
<tr>
<td>$\tau_c$</td>
<td>shear stress due to current</td>
</tr>
<tr>
<td>$\tau_m$</td>
<td>mean shear stress due to current and waves</td>
</tr>
<tr>
<td>$\tau_{max}$</td>
<td>maximum shear stress due to current and waves</td>
</tr>
<tr>
<td>$\tau_w$</td>
<td>shear stress due to waves</td>
</tr>
<tr>
<td>$\omega$</td>
<td>wave frequency</td>
</tr>
</tbody>
</table>

**Other symbols**

- $\mathbf{P}$ parameter dependency matrix
- $\mathbf{P}'$ parameter dependency matrix that is new for collaborative design
- $\mathbf{P}^-$ parameter dependency matrix of process outside design iteration
“[Large production volumes of future designs] can be realised through a strategy focused on producing continuous, incremental improvements in the current basic concepts of wind turbine systems. Besides this strategy ... the development of completely new concepts [is requested]. ... These two strategies should be developed in parallel.”

EWEA, 2009

1 Introduction

1.1 Challenges for technology development for offshore wind energy

1.1.1 Expectations and challenges for the developments

To date, the technical feasibility of making electricity from offshore wind energy has been convincingly proven. Since the installation of the first offshore wind turbine ‘Svante 1’ in 1990 cumulative installed capacity of offshore wind turbines in Europe has reached 4,995 MW at the end of 2012. Nowadays, offshore wind farms exist with an installed capacity of 630 MW, with up to 175 wind turbines. The individual power capacity of the turbines in these wind farms has grown from 220 kW to over 5 MW. The offshore wind farms include a variety of support structures, such as cylindrical towers, tripods and lattice towers, founded by (mono-) piles and gravity base structures. Strings of wind turbines are usually connected by cables to a central platform, where the typically AC electricity is stepped up to a higher voltage for transmission over a single cable to shore. These wind farms are installed using conventional vessels and jack-ups, modified offshore equipment and purpose-built vessels for instance for cable laying and pile driving, transport and installation of gravity bases and hoisting of towers and rotor-nacelle assemblies (RNA). Not despite various unanticipated early failures, there is now ample experience with procedures for transfer of personnel and exchange of major components. Improvements in both components and maintenance strategies have led to annual availabilities of over 95%. During 2012 electricity production of all European offshore wind farms together amounted to 18 TWh.

However, despite these achievements there is a need for improvement. First of all, the implementation of offshore wind farms is currently financially dependent of public support schemes. The duration of these incentives is finite and in the long run offshore wind energy needs to become competitive in the energy market under the same conditions as regular sources. Next, there are high expectations of the volume of electricity produced from offshore wind energy and various governments set ambitious targets for installed capacity at certain dates. It is questionable that these targets can be
met efficiently by simply duplicating the current approach many times. Other aspects that may require future changes are for instance environmental impact, sustainability and social acceptance, for which both understanding of the issues and establishment of the requirements have not yet reached a status quo.

There is much consensus that it is realistic to expect significant improvements in the performance of offshore wind farms and that these improvements can be achieved through replacement of components and procedures by alternatives that are based on different concepts or have major changes in principal attributes. This consensus is evidenced for instance by the abundance of suggestions for alternative concepts, the millions spent on research programmes to find such concepts, the numerous questions raised about this issue in professional settings, the actual development of new products by new companies and the lack of substantial contradiction. There is also a logical basis for the expectation of improvements. The current technical success of offshore wind energy is not in the least thanks to the developments of onshore wind turbines for the generation of electricity for over a century and more than half a century of developments in the offshore industry for applications such as surveying, drilling, oil & gas production, transmission and telecommunication. But despite the long track record of its parental industries, offshore wind energy is a relatively new application for the offshore industry and the offshore environment provides conditions in which wind energy technology hasn’t been applied before a few decades ago. Besides, the increase in scale already visible for wind turbines for offshore application leads to changes in its behaviour. Because the solutions from the parental industries are developed for other conditions it is unlikely that they are optimal for this newer application. Examples of the response of the wind turbine industry are the further increase of rated power of turbines that are developed for offshore application and the extra attention for reliability. An example of the response of the offshore industry to optimise their services to the needs of offshore wind energy is the development of vessel-type hoisting equipment with stabilising legs that have short logistic times and precise lifting capability at great height. The novel aspects of offshore wind energy set the technology further back on the learning curve and analogies with other technological developments show that this means more room for improvements. The phase of development of offshore wind farms supports the expectation that the chance of finding alternatives with significant benefits is worth the effort of investigation.

However, finding the solutions that lead to improvements is not trivial. From an engineering point of view, there are various challenges. First, new solutions need to comply with the demands, which are more stringent for offshore wind farms than for onshore wind farms. The harsh offshore environment raises demands on support structures, corrosion protection and climate control in the nacelle, while generally deteriorating working conditions. Second, the assessment whether new solutions meet the demands requires sufficient understanding of the involved phenomena, which is not always present. For instance, the stability of large diameter monopiles under high overturning loads was not relevant for conventional offshore structures and needed further investigation for offshore wind turbines. In general, the knowledge base for the assessment of new concepts is much smaller than the knowledge base for common technology. Third, the novelty of offshore wind farms effectively opens up a very wide range of alternative concepts. Mature technologies, progressed well along the learning curve, have evolved to a limited number of concepts and further progress is pursued
through smaller adaptations. This status quo has grown on design engineers, based on experience with things that work and things that don’t work in a certain environment. The changed environment and demands for offshore wind farms breaks the conditions for the status quo and leaves the design engineers with limited experience on which they can base their selections. Besides, the ocean provides working principles for support structures, transportation and hoisting equipment that are unprecedented onshore. Fourth, optimising solutions is more challenging than for onshore wind farms. The costs of an onshore wind farm are dominated by the wind turbine, so its optimisation can focus on that part of the system. Offshore, the wind turbines, support structures, electrical infrastructure, installation works and maintenance all provide significant contributions to the cost of energy. This means that optimisation involves many disciplines, different design teams in different companies and trade-offs involving different parts of the system. Last but not least, the design processes for the different contributions to an offshore wind farm are inherently asynchronous. Some of the major elements are designed to be used in many wind farms, e.g. the wind turbines, installation vessels and access vessels. Other elements are designed site specific, e.g. support structures and layout of the wind farm and electrical infrastructure. This further complicates optimisation of the system. In summary, the following five challenges for improvements in offshore wind energy technology are identified above:

- Design solutions need comply with the stringent demands of offshore conditions
- Good understanding of the physics is necessary to assess potential solutions
- Alternative concepts may perform better in this relatively new application
- Optimisation is difficult, due to the multidisciplinary and multi-component nature
- Design processes for general purpose and site specific components are asynchronous

The next section discusses which challenge requires new knowledge that can be aimed for in the current research project.

### 1.1.2 Identification of the challenge addressed in this research

The previous section argues the necessity and opportunities for improvements in technology for offshore wind energy, but also identifies several challenges. These challenges have been addressed by many earlier research projects. To identify the challenge to be addressed in the current research project, it is assessed which research directions complement previous work and which objectives are suitable to pursue in an academic environment. Therefore, this research started with an analysis of previous knowledge development for offshore wind energy technology. This review is presented in the journal Wind Energy. Before addressing the findings of that review, a brief history is given of related research of the group in which the work presented in this thesis is done. This helps the reader to understand the framework in which the research is done, which is one of the factors in the eventual selection of the challenge to be addressed.

The research group started to contribute to knowledge about offshore wind energy technology in the early nineties with the graduation project of Kühn to extend a wind turbine simulation tool with the capability to model the dynamics of an offshore wind turbine under hydrodynamic loading. This work contributed to facing the challenge to assess compliance of new solutions with the demands. Much of the subsequent work of
the group also contributed to assessment methods, with a strong focus on their suitability in the engineering design process. Another thread of work of the group used design case studies to generate potential solutions and to obtain their properties. The research of the group also aimed at design methodologies. The Opti-OWECS study paid attention to design methodology for offshore wind farms, with emphasis on dealing with the selection of alternative concepts in the multidisciplinary setting. Ecchavarría addressed similar challenges, but with the narrower perspective of the design of fault tolerant rotor-nacelle assemblies. This thread of work is much smaller in extent than the other two.

The work of others that is reviewed in the article in Wind Energy evidently covers a much wider range of topics. However, the nature of the work and the relative amount of effort spent on each type of research is very similar. The review concluded that many research activities contribute to foundational knowledge, needed to perform simulation and analysis of provisional design solutions. Most of the design-related studies are solution oriented and contribute to object- and context-related knowledge, particularly by means of case studies. A limited number of studies put more emphasis on methodologies. These studies largely target optimisation methods with a limited scope, such as for instance layout optimisation with respect to wake losses.

The review identified that conceptual change of the main sub-systems, which might have significant effects on the design of other sub-systems, is a potential area for technology development for offshore wind energy. Innovations that deviate from existing technology in small steps are most likely to be successfully implemented by existing companies, because these can build on previous in-house experience. There is a strong tradition in academic design research to complement this step-wise innovation with research of more radical conceptual variation, with the potential to lead to new industrial activities. The research of the current project originates in this tradition and therefore started with the aim “to establish potential concepts based on offshore requirements and to assess their properties, both advantageous and adverse.” An important aspect of the research would be the interaction of the various elements of a wind farm. However, the review showed that this type of work is very time consuming and therefore often limited in scope. The review didn’t lead to guidelines to narrow the scope of this type of research in the current project, particularly considering the already large number of alternative concepts under evaluation. Maintaining the wide scope as provided by the initial aim would imply a lower level of detail of the analyses, thus threatening the conclusiveness of the results.

The review also identified that industry is strong in technology development with a narrow scope, but that it has little support for the integration of their contributions in long-term offshore wind energy developments. This long-term development is based on many asynchronous design processes at various different companies, and several interactions between these design processes appear to be formed by market mechanisms rather than by design activities. The review concluded that previous activities brought integration into the picture by getting designers out of the companies into an integrated design project, but this failed to bring integration into the companies. New research could aim to stimulate technology developments inside companies by supporting design integration in their in-house processes. This could most effectively be done with
methodologies and tools that can be transferred from academics to industry and that contain the knowledge needed for integration.

The review acknowledged that the success of design integration studies is endangered if it doesn’t consider the challenges of integration in the asynchronous design processes of general purpose elements and site specific elements. Probably the design of the rotor-nacelle assembly suffers most from this challenge. The RNA is designed long before it is applied in an offshore wind farm. The standards used for this design process allow generic descriptions of the wind and other conditions to formulate and assess the constraints. When the wind turbine is selected by developers, the wind farm designer checks the compliance of the conditions at the targeted offshore site with the generic conditions used during the RNA design. This procedure effectively separates these two major design processes. It guarantees that the design constraints for the wind turbine are not violated, but it does not provide a means to optimise RNA design. This is a disadvantage, because the RNA has a large effect on the hardware and procedures designed in many downstream processes and on the final performance of the wind farm. This forces the RNA designers to anticipate how their product will affect the systems in which it will be applied in the future. Effectively, the turbine manufacturers get the burden of integrating their product into various different systems of which little is known at the time of designing. This integration is further complicated by the multidisciplinary nature of the system in which the RNA will be used.

Based on the outcome of the review it is chosen to target the methodological support of RNA design as regards the optimisation for later use in offshore wind farms. This addresses the challenge of optimisation of the multidisciplinary system in the context of asynchronous design processes, as presented by the last two bullets in the previous section. This direction leaves the originally intended explicit assessment of concepts, for the reasons discussed above, but maintains the focus on interaction of the elements of an offshore wind farm. Although the methodological support will target the process of designing the RNA, the earlier work done in the research group on offshore wind farms will be of much help to develop support for integration.

1.1.3 Theoretical support to meet the challenge

The author believes it to be helpful to construct the methodological support for rotor-nacelle assembly optimisation on a proper theoretical basis, rather than to work on the development from a practical starting point. This believe is supported by for instance the notion of Chong et al. that “[Computer Aided Design (CAD)] systems … call for a set of well-defined design theories to underlie their computational processes” and that “the success of technology-based design support systems … depends ultimately on the soundness of the design theories that they are based upon, if any at all”. This is further supported in the discussion of the applied approach in Chapter 2. However, theoretical considerations are associated with a more abstract formulation of the problem. Therefore, this section generalises the challenge for RNA optimisation to identify its essence and to discuss existing theoretical support.

The main challenge for the optimisation of the RNA is the asynchrony of the design processes, which hampers the possibilities for collaborative design. Also in some other system developments it can be observed that the design of its constituent elements is not
performed in a collaborative effort. Examples can be identified in developments of large scale socio-technical systems, such as infrastructure for energy supply. As stated by Bots, they “… are not designed and then constructed according to plan. Rather, they develop over a long period of time as a result of countless changes”.

Regarding Bots’ statement, it is useful to make a distinction between ‘design’ and ‘development’. For the purpose of this discussion, the distinction is defined by whether or not there is collaboration during the conception of the system. If there is collaboration it is called ‘collaborative design’ or simply a ‘design process’ and if there is no collaboration it is called a ‘non-collaborative development’. The word collaboration is defined in this context by:

**Collaboration is communication of intermediate design results between the initiation of a design project and its conclusion with a final design solution, with the purpose of updating information used for subsequent design activities.**

In this definition of collaboration it is essential that the communication is actively used in the iterative activities of the design process, based on the intermediate results. This excludes for instance communication between different sub-system designers to exchange general information. Such, potentially intensive and useful, contacts are not considered to be collaborative design in this thesis.

In a modular system, changes in a part of the system can cause changes in other parts and the properties of the system only come about when the elements of the system are put together. This also applies to a system that results from a non-collaborative development. However, it is questionable whether the currently applied scope in design processes effectively addresses this issue for non-collaborative developments. Current literature does not appear to provide guidance for system integration if it is not based on collaborative design. This is substantiated by for instance the taxonomy of product development as proposed by Ostergaard and Summers and models for design as proposed by Yazdani. With respect to organisation, all their categories and models assume collaboration, also for concurrent and asynchronous activities. All reviewed design research literature that deals with organisation either assumes collaboration or proposes to introduce collaboration. This observation is confirmed by Yadav et al., who classify product development literature into three key areas: design analysis activities, activity structuring and a coordination mechanism for a collaborative design framework. However, it is questionable that methods for formal collaboration are suitable for all non-collaborative development. For instance, the designers of rotor-nacelle assemblies do not collaborate formally (in a design process) with wind farm designers. The rotor-nacelle assemblies are designed for application in many wind farms and wind farm designers can choose from a selection of available rotor-nacelle assemblies. This flexibility and the difference between general purpose design of the rotor-nacelle assembly versus site specific design of the wind farm promote that collaborative design is not the predominant paradigm. Therefore, some non-collaborative developments need other means of support than can be provided by collaboration paradigms.

In the absence of system-level optimisation in non-collaborative development, commonly sub-system requirements are formulated to ensure compatibility with the rest
of the system and to try to reach optimality of the system. Although most design paradigms acknowledge the possibility to revisit the initial requirements based on feedback from design activities, this is generally not considered desirable. As such, requirements set boundaries on the design space and on what is considered optimal. Cross\textsuperscript{72} observed that “often, this boundary [used to define the function of the product or device] is defined too narrowly, with the result that only minor design changes can be made, rather than a radical rethinking”. In a non-collaborative development the ‘needs’ relate to the total system, rather than the sub system, and translating these needs to a sub set of requirements for the sub system may be particularly ineffective. This is confirmed by Fagerström and Jackson\textsuperscript{108}, who concluded that “the sub-supplier must have contextual knowledge of how the complete system operates”.

Defining requirements is an activity that takes place between product planning and synthesis of design solutions\textsuperscript{241, 277}. Being on this boundary, this activity can have a strong influence from marketing and strategic departments in a company\textsuperscript{121, 227} or from designers. As posed by Otto and Wood\textsuperscript{251}, a stronger influence of engineering on defining requirements can be observed in the design of highly technical products, which may have no market or customer needs analysis, but start with what he calls ‘understand requirements’ by engineers. Sub systems in non-collaborative developments are regularly highly technical products, but nevertheless the complex development setting promotes a strong strategic influence in fixing the requirements. Sheldon \textit{et al.}\textsuperscript{250} argued that a more central role of the engineering designer in the decision making process of senior managements leads to more competitive products. More specifically, Sheldon observed (in the eighties) that when designers have more means to analyse life-cycle costs and can exert more influence in the conceptual design phase, they can improve the trade-off between competitive edge and profitability. Pugh\textsuperscript{236} also made a plea for research on the cross coupling of engineering and marketing to achieve and maintain success in total design.

In summary, sub-system design results will affect system-level properties, but there is lack of guidance for system-level performance optimisation in non-collaborative developments. A common solution to this problem is to define sub-system requirements based on strategic decisions. Indeed, also for rotor-nacelle assemblies it appears that high level attributes, such as rated power, rotor diameter and service needs, are predominantly determined by marketing considerations. However, there are indications that better trade-offs can be made if the role of engineering is expanded in this situation. The challenge for the current research is to provide a theoretical basis and guidelines for a method that can achieve this better trade-off, particularly in the context of design of rotor-nacelle assemblies for offshore wind farms.

\section{1.2 The objectives of the research}

\subsection{1.2.1 Dual objectives}

The previous analysis identifies the practical challenge for the design of rotor-nacelle assemblies in Section 1.1.2 and translates this to a challenge formulated in abstract terms in Section 1.1.3. Following this analysis, the objective of this project is split in two parts. A first part of the objective addresses the abstract challenge to provide the theoretical basis and guidelines. This part is treated in Section 1.2.2. A second part of
the objective addresses the particular challenge for RNA design for offshore wind farms. This part is treated in Section 1.2.3. The separation of the objective in an abstract, theoretical part on the one hand and a practical, contextualised part on the other will remain visible throughout the thesis and in the conclusions. How these two parts of the objective appear in the approach and in the structure of the thesis is further explained in Chapter 2.

1.2.2 General and abstract formulation of the objective

The first part of the aim of this research is to obtain the principles of a method to improve system-level trade-offs in non-collaborative development without forcing collaboration between the sub-system designers, but with an increase in engineering contribution. Although this aim originates from the analysis of the design situation for rotor-nacelle assemblies for offshore wind farms, it is expected that the principles of this method are more generally applicable.

The principles of the method will be expressed in a design theory. The primary character of the theory is that it relates to the utility of the method. An impression of the typical general form of a theory about utility is given for management theory by Van Aken: “If you want to achieve Y in situation Z, then something like action [or artefact] X will help”. The addition ‘or artefact’ is made here to make the formulation more general. The formulation of Van Aken implies that the theory addresses the situation, the action or artefact and its helpfulness. For the theory of the current research the situation refers to the design process in a non-collaborative development, the artefact is the method to support it and the helpfulness is the improvement in the system-level trade-offs. The words ‘something like’ in the formulation of Van Aken imply that the design theory is not very explicit about the method, but rather captures its essential aspects.

The application of a method is realised through the use of instruments. Therefore, after deriving the principles of the method described above, the research addresses the sub-objective of obtaining principles for the implementation of such instruments. The implementation of such instruments is a design process, which consists of several activities. The principles for these activities are captured in guidelines. These guidelines are also part of the design theory. Further development of these guidelines may eventually result in a complete methodology for designing instruments for the proposed method, but for the current project completeness of the guidelines is not targeted.

A more detailed format for the theory, which captures both the principles of the method and of the implementation of an instrumental realisation, is provided in Chapter 3, where the theory is formulated.

1.2.3 Particularising the objective for offshore wind energy

When the general objective of Section 1.2.2 has been achieved, it provides the theoretical basis to develop a method to support the optimisation of the rotor-nacelle assembly for application in offshore wind farms. To obtain such a method is the second part of the objective of this research. A sub-objective for this part of the research is to achieve an instrumental implementation to apply the method. It is anticipated that this
implementation will be realised in a software tool and use cases that describe its application.

It is generally acknowledged that many methods and tools can coexist and that a designer should feel free to choose the most appropriate one each time, depending on the specific design problem at hand\textsuperscript{72, 97, 231, 241}. This implies that it is generally accepted that no unique best method or tool is available and that the suitability of a method depends on the design process in which it is used. This has two consequences for this research project. First, it has to be specified for which design processes the method and tool are applicable and this is actually used to narrow the scope of the research. Second, the development of the method and tool is a design activity in itself, since it is not a search for a true statement about how designing ‘is’, but rather a search for a method and tool that ‘work’.

The design process of interest that is selected for this project is the preliminary design phase of the rotor-nacelle assemblies. The novelty of the application of wind turbines at sea makes it more likely that changes in concept and main dimensions lead to better performance than for mature technological areas. These aspects are fixed in the preliminary design phase. Changes in concept and main dimensions can potentially have a large effect on other elements of the wind farm, through interactions. This means that system-level trade-offs cannot be made without proper knowledge of the effect of said interactions. As stated in Section 1.1.3, it appears that the high level definition of a new RNA is determined largely by marketing considerations. It is expected that this implies that limited quantitative information about system-level trade-offs is available in this phase. Furthermore, the role of qualitative reasoning, intuition, expectations and statistical analysis is expected to currently exceed the role of engineering. The purpose of the method is to expand the role of engineering and quantitative information in the high-level definition of a new RNA.

As explained above, the method that is aimed at supports the preliminary design of the RNA. However, the method will only address the issue of optimisation of the RNA regarding its future integration in an offshore wind farm. The method will have to be complemented by methods that are already in use by RNA designers. For instance, the assessment of loads in the blades, costs of manufacturing and reliability of the components should be done with existing methods. It should not be expected that the proposed method will comprehensively address all preliminary design aspects, since it doesn’t intend to provide a complete methodology for RNA design.

Although the method aims to supports the design process of rotor-nacelle assemblies, the instrumental implementation in the software tool is expected to contain much information about offshore wind farm design, as this is expected to be essential to address the issue of optimisation of the RNA for its use in a farm. This may cause some confusion, as it may lead to the expectation that the tool supports the offshore wind farm design process. Therefore, it is already emphasised here that the tool, although containing offshore wind farm design information, is meant to support RNA design and is not meant to support wind farm design.
1.3 **Approach of the work and layout of the thesis**

The purpose of this research is to contribute to knowledge about a new design method. Unlike research in natural science, this is not a pursuit of ‘truth’, but rather of ‘utility’, as can be seen in the discussion of the objective in Section 1.2.2. This type of research is often referred to as design research. Design research is a much younger discipline than natural science and its classification as a type of research can be considered to come from the original publication of Simon in 1969. This recent history of design research implies that there is less consensus about its methodology. Furthermore, different methodologies for design research coexist, leading to different types of outputs, as pointed out by e.g. Vaishnavi and Kuechler, Gregor and Jones and Järvinen. Therefore, different readers of this thesis may have different expectations of the approach and outcome of this research. To select an approach and to raise appropriate expectations, these are extensively discussed in Chapter 2. Topics that are discussed are the sequence of activities, the types of knowledge that are needed and generated and the types of output that are created.

The layout of the thesis follows the approach that is determined in the next chapter. Therefore, the layout is not presented here, at the end of the introduction, but it is presented in Section 2.5. Readers that are not interested in the discussion of the approach can immediately skip to Section 2.5 to see which further parts of the thesis may be of interest to them. Section 2.5 particularly identifies whether chapters in the thesis address general design theoretical aspects or particular contextual aspects of the support of RNA design for offshore wind farms.
“Our own experience has shown how both students and more experienced researchers struggle with the problem of expressing design knowledge in an acceptable form in theses and journal articles.”
Gregor and Jones, 2007

2 Organisation of the research

2.1 Purpose and methods of organising the research

As stated at the end of the previous chapter, different methodologies for design research coexist, leading to different types of outputs. The demarcation of this type of research as a scientific activity and the criteria for a scientific methodology in this field are subject of debate. On the one hand this provides some liberty to choose an approach that fits the purpose, but on the other hand any choice of approach can be opposed. The literature on this subject is used to select ideas that are appropriate for the current research, aiming as much as possible at common factors in different views. However, the purpose of this review is not to suggest best practices for design research. Rather, it leads to an approach that is considered to work well for this particular project. The discussion of the literature helps the reader identify the legitimacy and value of the chosen approach. Since much of the discussion is philosophical in nature, author names and quotes are often used to facilitate the identification of the source of the ideas.

In Section 2.2 literature about design research is reviewed, leading to the approach and the types of outcomes that are aimed at in this project. This project uses and develops knowledge about research, about design in general and about offshore wind energy. The roles of these three types of knowledge in this project are identified in Section 2.3. Given the formulated objective and approach, the academic position of the project is discussed in Section 2.4. Finally, Section 2.5 shows the layout of the thesis.

2.2 Selection of research approach

2.2.1 Classification of the research approach

According to Järvinen a taxonomy of research approaches can assist a researcher to find the best approach, using the research question to establish the appropriate class. The literature provides various taxonomies of research. A classification of this research project in terms of these taxonomies is established in as far as it helps identify which criteria and guidelines are relevant. Specifically, classes of research are identified for which the literature provides at least one of the following contributions:
- Provide guidelines for demarcation of routine work and academic work (Sections 2.1 and 2.4)
- Help choose between prescription or description of a design method (Section 2.2.2)
- Clarify appropriate expectations of the results (Section 2.2.3)
- Identify relevant research methods (Section 2.2.4)
- Provide guidelines to focus the research and to narrow the scope (Section 2.3)
- Support interpretation of the work by the reader (Sections 2.3 and 2.5)

One of the earlier classifications that distinguish research that aims at understanding reality and research that is concerned with devising artefacts to attain goals is that of Simon\textsuperscript{252}, published in its original version in 1969. The second type of research identified by Simon is widely acknowledged and in the field of engineering design it is usually referred to with the term design research. The current project can be classified as design research, since it is concerned with the development of a design method and its practical value. For correct interpretation of this classification of the research, it is essential to understand that the design method and the guidelines for implementation of instruments to apply it are the subjects of the research and not offshore wind energy technology per se. The research does not attempt to devise new offshore wind farms or related technologies. The classification as design research is supported by characteristics of design research provided in many papers\textsuperscript{101, 140, 155-158, 194, 273}. Several papers discuss design research in the context of research on information systems. Apart from the generic nature of most of the ideas, the relevance of these papers to the current project is also evident from the clarification of information systems as “complex organizations of hardware, software, procedures, data, and people, developed to address tasks faced by individuals and groups, typically within some organizational setting”\textsuperscript{194}. The targeted design method matches with this description.

According to March and Smith\textsuperscript{194} “design science consists of two basic activities, build and evaluate”. Elaborating on this idea, Järvinen\textsuperscript{156} introduces a class ‘researches stressing utility of artefacts’ that is differentiated into a class of ‘artefacts-building approaches’ and a class of ‘artefacts-evaluating approaches’. However, many sources consider building and evaluation as two essential and interacting parts of design research\textsuperscript{140, 146}. Since this project intends to test feasibility and effectiveness of elements of a newly devised design method and its associated instruments, both artefacts-building and artefacts-evaluating approaches are considered relevant to this project.

Kasanen\textsuperscript{169} uses the term constructive research for studies of “problem solving through the construction of models, diagrams, plans, organizations, etc.” in the field of management. The abstractly formulated ideas about this type of research have a wider range of application and are used for instance in computer science\textsuperscript{273}. The relevance of these ideas is also assessed for this project.

Zooming in on design research for industrial design engineering, Horváth\textsuperscript{146} identifies three framing methodologies for academic research: research in design context, design inclusive research and practice-based design research. The relevance of the domain discussed in this paper merits a closer look at these frameworks in order to identify the most appropriate. From the first to the last framework there is increasing integration of disciplines and knowledge of multiple domains and increasing contextualisation. In this project the context of design for offshore wind energy deployment is leading in the
problem statement. Furthermore, integration of designerly and fundamental knowledge as well as different types of fundamental knowledge are essential. This points in the direction of practice-based design research. However, this framework has disadvantages relating to both its methodology and the practical value of its outcome. The methodology leans heavily on product-oriented design activities, performed by designers and embedded in their natural environment. Horváth notes that “practice-based design research is considered a weak form of inquiry, and there is a strong debate concerning the value of practice-based output as a scientific research output”. Due to the high contextualisation the outcomes tend to be specific, rather than general. These are undesirable characteristics for this project, as it is performed in an academic environment and as the results can only be widely transferred to industry when they take a more general form. Research in design context generates generally applicable knowledge by applying classical methods of fundamental sciences to phenomena relating to artefacts, but this type of research is mono-disciplinary and more focused on understanding reality than on the utility of artefacts. Horváth notes that design inclusive research “integrates knowledge of multiple source domains, and lends itself to multidisciplinary insights, explanations and predictions, but can also generate knowledge, know how, and tools for problem solving”, which is desirable for this project.

In conclusion, design research for artefact-building and artefact-evaluation sets the methodological framework for this project. Details of the approach are guided by descriptions of design inclusive research. Parallels with constructive research, as used outside the domain of engineering design, are considered where applicable to identify widely acknowledged principles.

2.2.2 The main steps in the approach

Table 2-1 shows research activities or phases for the classes identified in Section 2.2.1 in as far as these are clearly and explicitly available in the discussed literature. The activities are horizontally aligned according to the objectives of the activities. Since action research has been associated with constructive research and with design science, its activities are included in the table.

Most classes define an explorative activity. Ignoring terminology and details, there is also large correspondence between the creative and evaluative phases of all classes. Overall, the outline of the activities fit this project: identify potential shortcomings in current design methods for offshore wind energy technology, propose and create a solution in the form of a new method and test how useful the method can be for practitioners in the offshore wind industry.

Of the analysed approaches only design (inclusive) research explicitly incorporates the development of a hypothesis and a design theory in its activities. Design science according to March and Smith actually denies the existence of such theories and claims that “rather than posing theories, design scientists strive to create models, methods, and implementations that are innovative and valuable”. The interpretation of design science by March and Smith and Järvinen as well as the activities shown for constructive research and action research correspond very well with the view expressed by Horváth on ‘practice-based design research’ (which is not included in Table 2-1). These approaches are very close to design or management processes in practice.
and designerly knowledge is created in a reflective manner by principles of learning by doing. Järvinen\textsuperscript{157} concludes that in design science “knowledge is generated, used and evaluated through the building action”, but no clear methodological foundation is provided for this type of knowledge creation. As discussed in Section 2.2.1, this type of approach has some undesirable characteristics for an academic project.

In light of the observed difference with design inclusive research, the lack of hypothesis and design theory is identified as a crucial factor in reducing the value of such approaches in an academic context. The validation of theory and propositions that provide predictions for the outcome of an experiment shows much resemblance to the common and widely accepted approach in natural science. Without hypothesis and theory there is less guidance in the (scientific) evaluation of the artefact and as noted by Harrison et al.\textsuperscript{135} “‘ad-hoc’ evaluation … with little or no scientific or objective assessment … exacerbates the academia/industry divide and delays technology transfer”. The hypothesis and theory development in design inclusive research is accompanied by a little more distance to the application domain of the creative phase, in order to acquire less contextualised knowledge. As discussed in Section 2.2.1 the domain of offshore wind energy is leading in the problem statement, but the quality of

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\textsuperscript{a} as quoted by Edelson\textsuperscript{101}

\textsuperscript{b} Step 1 is the development of a theory and step 2 is the derivation of principles for design from the theory.

\textsuperscript{c} These activities refer to natural science methods ‘… to determine why and how the artefact worked or did not work’\textsuperscript{194} in terms of natural laws. In contrast, theory and validation in design inclusive research may be concerned with propositions for non-physical concepts such as methods and methodologies.
the work and the potential for knowledge transfer are considered to outweigh the
disadvantage of a more general character of the results. Therefore, the induction and
deduction steps of design inclusive research are incorporated in this project. As a
consequence, the problems identified for offshore wind energy development need to be
formulated in more abstract and universal terms, as is done in Section 1.1.3.

An additional advantage of the formulation of hypotheses and theories in advance is that
this helps define the scope of the creative phase. Although a comprehensive new design
method may encompass many different aspects, only those aspects that are covered by
the hypotheses and theories need attention in the implementation of the instruments for
the method in this project. Various sources recognize the importance of reducing the
scope of the problem and solution\textsuperscript{184, 224, 273}. Cobb\textsuperscript{66} explicitly links the theory to the
creative phase by the derivation of principles for design from the theory. The software
tool and use cases that are designed and built in the creative phase are considered to be
instantiations to test the theory, following the line of thought of Newell and Simon\textsuperscript{217}
as quoted by March and Smith\textsuperscript{194} that “each new program [instantiation] that is built is
an experiment”. This experimental status of the instantiation is best captured by the use
of the word prototyping in design inclusive research.

The evaluation in design inclusive research is separated in verification and validation.
This appears to be a useful distinction to help interpretation of the results, but no clear
definition of the terms in this context is provided in the consulted literature. In this
project the separation of evaluation in two parts is interpreted as follows. As formulated
in Section 1.2 the research aims at a design method, with the sub-objective to obtain the
realisation of an instrumental implementation. The theory addresses the principles for
both the method and for the implementation of its instruments. In the creative phase this
is translated into a software tool and use cases. The separation of the evaluation is used
in this project to separate the evaluation of the software tool and the evaluation of the
use cases. The first part of the evaluation is used to check that the software tool works
as intended and to establish its performance. It should therefore provide confidence in
the trustworthiness of the tool. To avoid confusion with other interpretations of the
word ‘verification’, this activity will be referred to as ‘appraisal’. Validation is used to
refer to the use of the software tool in experiments, to collect information relating to the
utility of the method. The new knowledge created in the validation is considered the
most important outcome of the evaluation, as it is concerned with the aggregated
solution of the tool and its use. In short, the appraisal concerns the working of the tool
and the validation concerns its utility.

All approaches position the findings of the research in the framework of existing theory
and knowledge, although this is not shown for design inclusive research in Table 2-1.
Apart from design science according to March and Smith\textsuperscript{194} and Järvinen\textsuperscript{156}, all
approaches finish with an analysis of how the findings can be expanded to or interpreted
for other applications, thus exploring the scope of the theory. Although this is not
directly relevant to the research question of this project this will also help enlarging
acceptability of the results and may open the door to contributions from other
application domains. Therefore, this activity is incorporated in the approach of this
project. Instead, it is of special interest to this project to establish the relevance of the
findings for the offshore wind energy domain. This research originates in a practical
problem in the real world and an additional step is needed after this project to get from
the research results to a practical solution. An activity is therefore added to the approach to look at the prospect for such practical solutions and this is referred to as contextualisation.

Figure 2-1 gives the final activities in the research approach, alongside an indication of the output per activity. The activities and output are further clarified in Section 2.2.3. The following adaptations are made with respect to the original diagram for design inclusive research:

- The steps ‘conception, design and prototyping’ are condensed in the phase ‘creation’ and will be expanded during execution of that phase
- The activity ‘appraisal’ replaces the activity ‘verification’, as per the interpretation given above. The output ‘confidence’ replaces the output ‘proof’, since the word ‘proof’ is considered inappropriately conclusive in empirical research
- The step ‘contextualisation’ is added, building on ‘validation’ results and information about the prototype

### 2.2.3 Clarification of activities and expected results

Figure 2-1 of the previous section provides keywords for the activities and outputs. This section clarifies these keywords and gives the interpretation for this project.

**Exploration and Observation**

Previous activities that aimed to improve development of technology for offshore wind energy are explored in order to identify bottlenecks that appear to hamper the discovery
and introduction of technological improvements. Because of the objective of this project an engineering point of view is taken, rather than for instance a management point of view. The observed bottlenecks can be very specific for specific activities. To enable a contribution of academic research to alleviate the problem, an abstraction of the bottlenecks is formulated.

**Induction and Hypothesis**

This phase uses an analysis of the origin of the bottlenecks and existing knowledge to hypothesise solutions that may alleviate the problems. Two basic types of hypothesis are generally encountered in literature: 1. the hypothesis that a direction for a solution will lead to an artefact that works or 2: the hypothesis that a direction for a solution will lead to an artefact that works better than another solution. For several sources the types of hypothesis are concluded from the formulation of possible research questions or from the description of the type of results. Which type of hypothesis is formulated in this project depends on the maturity of the proposed solution and the possibility to evaluate reference solutions. Due to the novelty of the targeted research area, it is anticipated that most hypotheses in this project focus on feasibility of a solution, rather than on its relative performance. The activity to generate the hypotheses may prove hard to describe. As noted by Roozenburg and Eekels, “how the process [of induction] really proceeds is not clear”. A governing hypothesis in this project is that a new design method can be devised to support design of offshore wind energy technology, as formulated in Section 1.1.2. Several more detailed and less comprehensive hypotheses are formulated in this phase to separate the issues.

**Deduction and Theory**

The development of a design theory is the core of this project, as the theory represents potentially durable and reusable knowledge. The principle of theory building by compilation of existing knowledge is applied. Based on the problem description and the hypothesis, previous (design) knowledge is searched and combined to give a theoretical model of the solution. To ensure appropriate expectations of the activities and the developed theories, the following issues are mentioned:

- Although the use of existing knowledge in a deductive process is pursued, existing knowledge may appear incomplete for the purpose of this work. In such cases inductive reasoning and consequential hypothesised elements may be included in the theory. Such elements require more elaborate validation for acceptance, for which the scope of this project may prove too limited.
- “Design science research is perishable, as technology advances rapidly” and it is inappropriate to “assume the existence of a complete, consistent specification”. The design theory may be more time-bound than a theory in natural science.
- In order to enable validation of the design theory, testable propositions are defined that address feasibility and effectiveness of certain solutions. The design theory addresses utility, rather than truth and it proposes that something works or how well it works, rather than why and how it works. Theorizing why and how things work is not the focus of this project, although previous knowledge is used in developing the design theory.
- It is chosen to make a prescriptive design theory. According to several sources, models should be prescriptive and methods should be normative. Since this
project intends to provide guidance for a new design method the prescriptive nature of this design theory is appropriate. To avoid confusion, it is emphasised that a prescriptive model doesn’t force a designer to use it, but rather provides a designer with a well documented and possibly tested option. In contrast, normative methods prescribe what ‘ought to’ be done\textsuperscript{155}, rather than what can be done.

**Creation and Prototype**

The theory developed in the previous phase provides principles for design of a method to support sub-supplier design in a non-collaborative environment. This level of abstraction provides the theory its wide scope. To test the theory, the principles of form and function need to be applied in a practical design solution. The creation phase designs and implements an instrument to apply the design method for offshore wind energy technology. The instrument entails a software tool and procedures to use them. It is anticipated that particularly the tool contains knowledge from the context provided by offshore wind energy. Both the tool and the procedures use design methodological knowledge of a more universal nature. The created tool is not intended to be comprehensive. Since it is designed as a prototype, the theory and its propositions determine which aspects are covered by it. Further development of the tool before it can be applied in practice is assessed in the contextualisation activity.

Some sources identify the artefact designed in a building process as a major output of a design research project. For instance the line of thinking presented by March and Smith\textsuperscript{194} and Järvinen\textsuperscript{155} puts emphasis on constructs, models, methods and instantiations as outputs. In this project the instantiation of the instrument to apply the design method is not a key output. Its creation is subservient to the objective of theory building and testing the propositions of the theory as proposed by Gregor and Jones\textsuperscript{125} and Horváth\textsuperscript{146}.

**Appraisal and Confidence**

According to Horváth\textsuperscript{147} one of the open issues of design inclusive research is that “the knowledge generated by the design activities is idiosyncratic, therefore it conveys limited verification and generalisation power”. In other words, the indispensable contextualisation during the creative phase pollutes the prototype of the tool as an instrument to test the theory. In addition to this pollution, errors in modelling and implementing domain specific knowledge may influence results found during validation of the theory. To eliminate the latter type of influence as much as possible the implemented tool is appraised with data of existing offshore wind farms. The basic appraising activity is comparison of known information about existing wind farms with outcomes of isolated parts of the tool. Analysis of the differences between the tool and reality provides a confidence level of the incorporation of the domain specific knowledge.

**Validation and Evaluation**

The validation activity uses the appraised instantiation of the tool for offshore wind energy as an instrument to test the propositions in the theory. Examples of design evaluation methods given by Järvinen\textsuperscript{156} are case studies (in-depth study of the artefact in a business environment), controlled experiments (study of qualities of the artefact in a
laboratory set-up) and informed argument (building a convincing argument for the artefacts utility). Since the hypotheses in this project are anticipated to focus on feasibility, the propositions are also expected to relate to working principles, rather than relative performance of the method. As a consequence, the evaluation is expected to reveal more qualitative information than quantitative information. It is noted that the tool that is applied in the method may have a strong quantitative basis, which is formed by the domain specific knowledge of offshore wind energy. However, most quantitative insight this provides is domain specific and is used in the appraising activity.

**Consolidation and Generalisation**

The theory aims to be useful for many applications and for a long period of time. However, the propositions in the theory are only tested in a specific, developing design context. The purpose of the consolidation activity is to generalise the results of the validation to other applications in order to assess the validity of the theory in other contexts. The result of this activity should be a founded specification of the purpose and scope of the design theory. However, no rigorous means to achieve this are known to the author. Dorst calls design methodology “pseudo-scientific in the sense that some of the knowledge in this field cannot be generalised and verified to the standards of normal (positivistic) science”. Furthermore, consolidation includes “matching [the results] against the existing body of knowledge”\(^{147}\). Therefore, common sense is the basic instrument in this activity, for instance to analyse which domain specific aspects may have influenced the validation results. In the end, usefulness of the theory in other applications needs to be tested in the context of these applications. The consolidation activity focuses on listing properties of the design context that appear favourable or disadvantageous to successful application of the theory.

**Contextualisation and Prospect**

The results of this project do not provide a ready-to-use solution to the problem that initiated the work. The desire to support technology development for offshore wind energy is re-formulated in more abstract terms to derive hypotheses and theories that could be more universally applicable. The tool created to test the theory is dedicated to offshore wind energy, but it is an incomprehensive prototype. Several steps need to be taken to create a solution that is useful in a business context. The contextualisation activity aims to provide insight in which fundamental and practical issues need to be addressed in further developments and which opportunities and threats are foreseen, in order to assess further required effort and chance of success.

**2.2.4 Selection of research methods**

The research approach developed in Section 2.2.2 and the description of activities and outputs given in Section 2.2.3 provide guidance for the selection of methods to be applied in the research phases. Järvinen\(^ {156}\) even defines “a research approach as a set of research methods that can be applied to the similar research objects and research questions”. An association of methods with each of the individual phases in the approach is more generally observed in literature. Various sources that present the approaches discussed in Section 2.2.2 recommend certain methods for certain phases\(^ {140, 156, 184, 224}\). Using the abstract formulation of the phases, many alternative methods that are associated with the intended activity can be found in other sources.
However, the development of the project is too unknown to select appropriate methods for all activities in advance. Since formulation of hypotheses and theories are part of the work, it can progress in many directions. According to Sim et al.251 “Petre [recommends] using the nature of evidence required as a basis for designing a study”. This means that the validation methods depend on the type of propositions made in the explorative phase. There is an additional effect of uncertainty about the development of the project associated with the inclusion of design activities in the research. As stated by Horváth147, “for the reason that the research means are dynamically evolving and that they provide immediate feedback for the researchers, they may influence the research actions in design inclusive research”.

Given the wide scope of the research, it is anticipated that both qualitative and quantitative methods need to be considered, depending on the desired type of results. Furthermore, design methods are needed in the creative phase. The applied methods are described at the relevant places in the thesis.

2.3 Roles of research, design and offshore wind energy

Section 2.2 describes the research process, which includes aspects of research, design and offshore wind energy. This section discusses the role of these three elements in this project. This provides further understanding of the activities and outputs that are discussed in Sections 2.2.2 and 2.2.3.

According to Hevner et al.140 design research is positioned between an environment and a knowledge base as illustrated in Figure 2-2. This framework is useful to recognise the relations between this research project and external aspects. Companies involved in offshore wind energy technology constitute the environment that provides relevance, particularly when observations are made and hypotheses are formulated. The knowledge base provides knowledge for all activities in this project while particularly appraisal, validation, consolidation and contextualisation generate additions to the knowledge base. Hevner et al. do not elaborate on the meaning of application of the research output in the environment as indicated bottom-left in the diagram. This part of the framework is not recognised in the current project. The prototype of the tool that is made in the creative phase can be tested in companies or in a related experimental setting as part of the research activities, but the prototype is not intended to be an artefact ready to use in the environment. Rather, the research aims to provide additions to the knowledge base that can be applied in the environment as indicated by the added dashed line. The applicability of this knowledge in companies involved in offshore wind energy technology is assessed in the contextualisation activity, while the applicability in other environments is assessed in the consolidation activity.

Where the environment provides only the relevance for the research, the interaction between the research activities and the knowledge base is much more intense and this merits closer inspection. The four activities of research shown in the centre of the framework originate from March and Smith194, although Hevner et al.140 reword ‘Theorize’ with ‘Develop’. As illustrated in Table 2-1, these activities match only partly with the design inclusive research activities adopted for this project. Therefore, the activities given in Figure 2-1 are only used to describe the interactions with the
The knowledge base in Figure 2-2 is subdivided in foundations and methodologies. Since the purpose of this section is to clarify the roles of research, design and offshore wind energy in this project, a different subdivision of the knowledge base is used. Horváth identifies three bodies of knowledge used in design inclusive research: research methodological knowledge, design methodological knowledge and object- and context related design knowledge. Interpreting the last type of knowledge as offshore wind energy knowledge, the relation between the knowledge base and the project activities and outputs is illustrated in Figure 2-3. Offshore wind energy knowledge includes all types of knowledge about design, physics, behaviour, economics, etc. as far as it concerns its specific application in this domain.

The position of an activity in a body of knowledge indicates the type of knowledge used to perform the activity. The rigour of the adopted approach is clearly illustrated by the figure, since most activities are based on research methodological knowledge, including the planning activity. However, it is noted from the descriptions in Section 2.2.3 that induction, consolidation and contextualisation do not have a strong rigorous base. The creation activity, in which the instrument for the method is instantiated, is based on design methodological knowledge. It is emphasised that designing offshore wind energy technology is not an activity of this research approach, but that object- and context related knowledge of offshore wind energy is nevertheless a necessary input for the tool that is developed for the method.

The position of an output in a body of knowledge indicates the type of existing knowledge that is synthesised or the type of new knowledge that is brought about in the output. This means that it represents both the knowledge input and the knowledge output of an activity. Consider as an example the planning of the research approach in the previous section, which is a synthesis of existing (design) research knowledge. The type of input and output knowledge in this project meanders between design methodological knowledge and offshore wind energy knowledge. The observations are based on exploration of wind energy knowledge, but an abstraction is made to get
hypotheses and theory based on more generally applicable design knowledge. The prototype of the tool uses both generic design knowledge and offshore wind energy knowledge, as it is designed to test the generic theory, but it needs a context for its instantiation. The evaluation can highlight the generic knowledge, because the appraisal provides the confidence in the offshore wind energy knowledge used in the prototype. Nevertheless, the context will still influence the evaluation to some extent. The outcome of the validation is extrapolated using generic design knowledge to obtain insight in the general value of the design theory in various applications. An extrapolation of the evaluation using offshore wind energy knowledge leads to a prospect for application in the offshore wind energy domain.

In summary, research knowledge is used in the project to shape the activities in a rigorous way. Generic design knowledge is used to shape the creation activity and to provide information to assess how generally applicable the results are. The offshore wind energy domain provides relevance to the activities and knowledge content for the problem identification, the prototype of the tool and the prospect of a solution for the initially observed problems for offshore wind energy using the newly developed general knowledge. The project aims to extend the body of design methodological knowledge, while extension of offshore wind energy knowledge is obtained from the development, use and evaluation of the tool.
2.4 Assessment of academic position of the project

The first sections of this chapter describe a process that leads to the research approach and expectations about the type of results of this project. Justifications to do the work in an academic context and the relevance of the work to the wind energy community are used to guide decisions in this process, although this is not always explicitly discussed. This section reflects on the chosen problem definition and research approach to describe how it provides academic quality and practical value.

This work has several characteristics that make it better positioned in a research institute than in a business environment. First, to address the long term development of offshore wind energy, including all its contributing technologies, exceeds the scope of each of the involved business entities. Second, the existing knowledge base appears to be either insufficient, or insufficiently tested to create a tool to apply the method for offshore wind energy technology. Extension of the knowledge base is more objective when academic methods are applied by an independent researcher. Third, applying design methods that address the interactions and integration of the elements of offshore wind energy is currently not routine. The uncertainty of the benefits of such design methods and the risk that they cannot be implemented successfully are fairly large. These three characteristics match the benefits of academic design research as indicated by Cooper and Press\textsuperscript{69} to be: ‘Wider perspectives’, ‘rigour’ and ‘risk and adventure’.

The project needs design knowledge about offshore wind energy to develop the prototype of the tool and its use cases. This design knowledge is less available in a research institute than in a company. However, the function of the prototype as an experimental facility reduces the demands on domain specific design knowledge.

Academic quality is ensured in the first place by application of research methodological knowledge, as illustrated in Figure 2-3 in Section 2.3. Established academic methods are selected for most activities. However, it is also noted that there is a less rigorous base for the activities induction, consolidation and contextualisation. Furthermore, various sources bring up the inadequacy of current knowledge about research methodologies to generate design knowledge\textsuperscript{140, 147, 194, 251}. Open issues are not resolved in this project, but the explicit discussion of the approach facilitates assessment of the work by the reader. Because of the dynamics of the philosophy of design research, the inclusion of various contemporary sources ensures that state-of-the-art knowledge is applied in the definition of the research approach. The approach still leaves much freedom and uncertainty about the content of the work, such as the direction to be taken with the hypotheses and the feedback obtained from intermediate results. However, the freedom to just design and see what can be learned from that is taken away, at the benefit of a higher quality. Special effort is made to ground the work in ‘tried and true’ methods and methodologies (as far as available for this kind of research). Particularly with respect to methodology, the author perceives that this foundation is stronger than in much other design research in the field of wind energy. Cobb\textsuperscript{66} (as quoted by Edelson\textsuperscript{101}) even questions whether or not such a process is ever realised in practice, although Horváth\textsuperscript{147} notes that many PhD’s instinctively apply one of the three methodological frameworks he identified\textsuperscript{146}, but do not refer to it explicitly.
Several articles discuss criteria for design research, to distinguish routine design from design research, to establish design research as a science or to provide guidelines for effective research. The design science research guidelines presented by Hevner et al. 140 form a clearly explained list that covers most of the criteria found in other sources. This list is reproduced in Table 2-2 and is used to assess whether the current project can potentially meet these guidelines.

Guidelines 1 and 2 express the need to produce an artefact, with the objective to develop solutions for relevant problems. The artefact produced by this project is the prototype of the tool and its use cases. However, it doesn’t have the same stature as expressed in guideline 1. Gregor and Jones 125 notice that emphasis on the central role of the artefact is a common element in different design research approaches, but that others construct the artefact as a ‘test’ of design theory. The latter approach is adopted in this project. The objective of this project is therefore not to develop solutions, but rather to establish design theory. Relevance is incorporated as discussed in Section 2.3. Guideline 3 is covered by appraisal and validation, although also here the emphasis is on utility, quality and efficacy of the design theory, rather than on the particular instantiation of the prototype. Section 2.2.3 provides information about the research contributions mentioned in guideline 4 by describing the expected outputs. The emphasis of this project is on contributions to design foundations. The research rigour applied in this project covers not only the construction and evaluation of the artefact, as expressed in guideline 5, but also the set-up of the research and the other defined activities. As discussed earlier in this section, some issues of research rigour are unresolved. Since the artefact in this project is a prototype for a ‘test’, it is created in a design process as indicated by guideline 6, but only with a limited number of search iterations. The structure of this project lends itself for effective communication to different audiences, as intended by guideline 7. This is further clarified in the next section, where the structure of the thesis is presented.

<table>
<thead>
<tr>
<th>Guideline</th>
<th>Description</th>
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<tbody>
<tr>
<td>1. Design as an artefact</td>
<td>Design-science research must produce a viable artefact in the form of a construct, a model, a method, or an instantiation</td>
</tr>
<tr>
<td>2. Problem relevance</td>
<td>The objective of design-science research is to develop technology-based solutions to important and relevant business problems</td>
</tr>
<tr>
<td>3. Design evaluation</td>
<td>The utility, quality, and efficacy of a design artefact must be rigorously demonstrated via well-executed methods</td>
</tr>
<tr>
<td>4. Research contributions</td>
<td>Effective design-science research must provide clear and verifiable contributions in the areas of the design artefact, design foundations, and/or design methodologies</td>
</tr>
<tr>
<td>5. Research rigour</td>
<td>Design-science research relies upon the application of rigorous methods in both the construction and evaluation of the design artefact</td>
</tr>
<tr>
<td>6. Design as a search process</td>
<td>The search of an effective artefact requires utilising available means to reach desired ends while satisfying laws in the problem environment</td>
</tr>
<tr>
<td>7. Communication of research</td>
<td>Design-science research must be presented effectively both to technology-oriented as well as management-oriented audiences</td>
</tr>
</tbody>
</table>
2.5 Outline of the thesis

The chapters of this thesis are set up as illustrated in Figure 2-4. The set-up of the research given in Section 2.2 provides a logical order for presentation of the work and findings of this project. Mostly, each of the steps in the approach is documented in a separate chapter. However, the formulation of hypotheses is distributed over two different chapters. Hypotheses about the blueprint of the method are reported in the chapter that describes the design theory. In addition, several hypotheses are needed when the theory is implemented for offshore wind energy. These hypotheses are reported in the chapter about the implementation of the prototype. The consolidation and contextualisation are merged into one chapter, but in separate sections.

The placemat below the layout of this thesis in Figure 2-4 is based on Figure 2-3. This helps to identify which parts of the thesis may be of interest to whom. The outcomes of this project are deemed valuable to two groups of people. The first group consists of people working in offshore wind energy, both designers, managers and researchers. Particularly the outcomes at the right-hand side of Figure 2-3 are of interest to this group. The observations are made in the domain of offshore wind energy and the prototype is created and appraised for this domain. Since the prototype comprises only solutions for part of the observations, the prospect reconnects the intermediate outcomes with the original observations. This subset of outcomes provides better understanding of the possibilities for design methods and tools for the offshore wind energy domain. The second group consists of a broader group of designers and design researchers, including...
those from the first group. The outcomes in the centre of Figure 2-3 are of interest to this group, as these contribute to more general knowledge to deal with design processes that share certain characteristics. This subset of outcomes forms a range from hypotheses to validation.

Readers that are interested in design in general may read Chapters 2, 3 and 6 and focus on the section on consolidation in Chapter 7. Readers that are interested in the offshore wind energy issues in particular may read Chapters 4, 5 and 6 and focus on the section on contextualisation in Chapter 7. The conclusions in Chapter 8 may again be of interest to all readers and separate conclusions about the theory from those about the implementation for offshore wind energy.
3 Theory for a method to support sub-suppliers in non-collaborative development

3.1 Purpose and methods of theorising

3.1.1 Purpose of the theory

Chapters 1 and 2 argue the need of a design theory as a basis. The purpose of the design theory is to provide guidelines about the principles of methods to support non-collaborative developments in general. The theory doesn’t explicitly describe a design method, but rather the principles to design a method for a specific context. By capturing the essence of the method in an abstract formulation, as opposed to the concrete description of its application in a practical situation, the theory enables designers from very different backgrounds to create methods for a variety of application domains.

As stated in the brief description of the design theory in Section 2.2.3 it is prescriptive. This means that it can be used as a recipe, albeit in abstract wording that require interpretation and translation to create a method for a specific application. Another purpose of the design theory is to provide the documentation that enables designers to decide whether the proposed approach is appropriate for them.

3.1.2 Components of the design theory

Gregor and Jones\textsuperscript{125} provide a template for design theory that acknowledges differences between natural science and science for design. This template, as copied in Table 3-1, is applied in this project. Although this template is originally developed for theories about information systems, the components appear appropriate for design theories in a more general context.

The template divides the components of the design theory in two categories: the core components and the additional components. The core components provide the actual abstract formulation of the theory, which gives it its wide scope. Component 6, the justificatory knowledge, is not presented as a separate component. Instead, justificatory knowledge is provided for each of the other components at the relevant points in the text. The additional components provide the link between theory and practice. The
principles of implementation provide a starting point to put the theory into practice and as a spin-off this helps to interpret practical implications of the theory. The expository instantiation can be used in experiments to test the theory. Component 2-7 are formulated in this chapter, whereas component 8 relates to the creative phase that is reported in Chapter 4.

3.1.3 Principles of theorising

In this project, theorising starts with the derivation of an abstract representation of the process in which the method will be applied, resulting in a descriptive model of design in a non-collaborative development. This model is compared with a model of collaborative design, which is expected to yield better solutions, leading to an assessment of deficiencies in non-collaborative development. The elimination of these deficiencies becomes the purpose of the theory, component 1. Analysis of what is expected from the method to eliminate these deficiencies leads to the form and function in the theory, component 3. Component 7, the principles of implementation, is derived from an analysis of what needs to be done to refine and reduce the functional requirements as well as a literature study for potential building blocks to fulfil these functions.

The principles of theorising resemble a design process, because the theory in itself is an artefact with utility. The inductive reasoning in this process does not preserve truth of statements and hence the logical status of the final theory is undefined at this point. The

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Table 3-1 Eight components of an information systems (IS) design theory\textsuperscript{125}

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
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<tbody>
<tr>
<td>1. Purpose and scope (the causa finalis)</td>
<td>“What the system is for,” the set of meta-requirements or goals that specifies the type of artefact to which the theory applies and in conjunction also defines the scope, or boundaries, of the theory</td>
</tr>
<tr>
<td>2. Constructs (the causa materialis)</td>
<td>Representations of the entities of interest in the theory</td>
</tr>
<tr>
<td>3. Principle of form and function (the causa formalis)</td>
<td>The abstract “blueprint” or architecture that describes an IS artefact, either product or method/intervention</td>
</tr>
<tr>
<td>4. Artefact mutability</td>
<td>The changes in state of the artefact anticipated in the theory, that is, what degree of artefact change is encompassed by the theory</td>
</tr>
<tr>
<td>5. Testable propositions</td>
<td>Truth statements about the design theory</td>
</tr>
<tr>
<td>6. Justificatory knowledge</td>
<td>The underlying knowledge or theory from the natural or social or design sciences that gives a basis and explanation for the design (kernel theories)</td>
</tr>
<tr>
<td>7. Principles of implementation (the causa efficiens)</td>
<td>A description of processes for implementing the theory (either product or method) in specific contexts</td>
</tr>
<tr>
<td>8. Expository instantiation</td>
<td>A physical implementation of the artefact that can assist in representing the theory both as an expository device and for purposes of testing</td>
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</table>
design process does not necessarily lead to the best solution and therefore the utility of the proposed method is also undefined. Therefore, the propositions, component 5, are formulated as a starting point to test validity and utility of the statements in the theory.

3.1.4 Layout of this chapter
The consecutive sections treat the various components of the developed design theory according to Table 3-1. However, first Section 3.2 analyses the non-collaborative development of systems from an engineering perspective. This section presents a descriptive model of non-collaborative development that provides a basis for the development of the theory. The identification of the scope and purpose of the method as well as the principles of form and function of its instruments are reported in Section 3.3. Section 3.4 treats the principles of implementation of the instruments of the method. Mutability and testable propositions are discussed in Section 3.5. The constructs provide the terminology and definitions pertaining to the theory and these are given in Appendix A. Terms that are explained in Appendix A are printed in italic at their first appearance in the text after this introduction to help identify them.

3.2 Formal representation of non-collaborative development

3.2.1 State-space model for purposeful action
As starting point, it is desirable to have a model of a non-collaborative development, in which the role of sub-system design and collaboration can be identified. Roozenburg and Eekels\textsuperscript{241} describe the principles of purposeful action as intervention in the natural development of states in the domain of material reality following thought processes in the domain of the mind. Inspired by their description, a state-space representation of the domain of material reality and of the mind is chosen as foundation for the model. Figure 3-1 illustrates the model and shows how the different domains are assumed to be related. The figure shows \( n \) individuals and the \( x, u \) and \( y \) symbolise state vectors, inputs and outputs, respectively. The figure also defines the meaning of the indices. The output of the domain of reality provides the input for the domains of the mind and the outputs of the domains of the mind are cumulative inputs for the domain of reality.

Each of the domains in Figure 3-1 is described with state-space equations for a non-linear, continuous time system:

\[
\begin{align*}
\dot{x}(t) &= f(t, x(t), u(t)) \\
y(t) &= g(t, x(t), u(t))
\end{align*}
\] (3-1)

When the time derivative of a state parameter is interpreted as its change, rather than its stricter meaning of gradient, the equation also represents discontinuous changes in the state. To identify patterns in the induction of state changes in one domain by another domain, the coupled state-space equations are expressed in a matrix notation. The matrix notation uses an operator \( H \), which is defined by:
meaning that the operator identifies which parameters are an element of the function. Using the definition of operator $H$, its rules for multiplication and summation become:

$$0 + H = H; \ 0 \cdot H = 0; \ H + H = H \cdot H = H - H = \frac{H}{H} = (H \vee 0)$$ (3-3)

The use of operator $H$ is illustrated by the following example:

$$y = Hx \rightarrow \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} 0 & H \\ H & H \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \iff y_1 = 0 \cdot x_1 + H \cdot x_2 = f_1(x_2)$$

$$y_2 = f_2(x_1, x_2)$$ (3-4)

When the time dependency is not shown explicitly, the state-space equations become:

$$\dot{x} = Ax + Bu$$

$$y = Cx + Du$$ (3-5)

in which the appropriate elements of matrices $A$, $B$, $C$ and $D$ contain the operator $H$ to express the functional dependencies.

Rewriting the state-space equations for all domains in matrix notation, connecting the inputs and outputs according to Figure 3-1 and using the calculation rules for $H$, leads to the following matrix form state-space model:
\[
\begin{bmatrix}
\dot{x}'_r \\
\dot{x}'_{m,1} \\
\dot{x}'_{m,2} \\
\vdots \\
\dot{x}'_{m,n}
\end{bmatrix}
= 
\begin{bmatrix}
A'_r & B'_{r,1} & B'_{r,2} & \cdots & B'_{r,n} \\
B'_{m,1} & A'_{m,1} & 0 & \cdots & 0 \\
B'_{m,2} & 0 & A'_{m,2} & \ddots & \vdots \\
\vdots & \vdots & \ddots & \ddots & 0 \\
B'_{m,n} & 0 & \cdots & 0 & A'_{m,n}
\end{bmatrix}
\begin{bmatrix}
x'_r \\
x'_{m,1} \\
x'_{m,2} \\
\vdots \\
x'_{m,n}
\end{bmatrix}
\]  

(3-6)

in which:

\[x' = \begin{bmatrix} x \\ u \end{bmatrix} = \text{combined vector of state parameters and output parameters},\]

\[A'_r = \begin{bmatrix} A_r & 0 \end{bmatrix} = \text{self-affecting process for domain } r \text{ (physical and chemical)},\]

\[A''_m = \begin{bmatrix} A_m & 0 \end{bmatrix} = \text{self-affecting process for domain } m \text{ (cognitive)},\]

\[B'_r = B_r \begin{bmatrix} C_r & D_r \end{bmatrix} = \text{cross-domain effect from domain } r \text{ to domain } m,\]

\[B''_m = B_m \begin{bmatrix} C_r & D_r \end{bmatrix} = \text{cross-domain effect from domain } m \text{ to domain } r.\]

The cross-domain effects include imperfections caused by either the originator (\(C\) and \(D\) matrices) or the subject (\(B\) matrix).

The computational rules of algebra combined with those of operator \(H\), enable various manipulations of Equation (3-6) such as merging sub-vectors, splitting sub-vectors and swapping positions of sub-vectors. These manipulations affect the structure of the state transition matrix. Since this structure is the most important aspect of this model for the purpose of this research the following graphical notation is defined for the state-space model:

\[
\begin{bmatrix}
\dot{x}'_1 \\
\dot{x}'_2 \\
\dot{x}'_3
\end{bmatrix}
= 
\begin{bmatrix} A & B & 0 \\ 0 & A & 0 \\ B & 0 & A \end{bmatrix}
\begin{bmatrix} x'_1 \\ x'_2 \\ x'_3 \end{bmatrix}
\]

(3-7)

The shape and meaning of the state transition matrix in its graphical notation has much in common with the Design Structure Matrix (DSM)\(^{103, 312}\). However, the DSM is typically used to represent the self-affecting and cross-coupling effects of different parts of a system that is being designed. Here, the state transition matrix shows the processes in the design activity. The squares on the right-hand side of Equation (3-7) can be replaced by other symbols to identify specific elements in the matrix.

### 3.2.2 Model for non-collaborative development

As mentioned in the previous section, it is desirable that the models helps to identify the role of collaboration and therefore of communication. The pattern in Equation (3-6) reflects that state parameters of one mind can only induce state changes in another mind indirectly through their effect on state parameters in the domain of material reality. Therefore, the state vector of the domain of material reality can be divided in parameters that represent physical states and parameters that represent the expressions
of the domain of the mind in the domain of material reality. Such expressions are for instance text in the form of ink on a paper, value in the form of numbers on a banknote and Newton’s law in the form of code in software. By further dividing the state vector of material expressions of the domain of the mind, the pattern of the transition matrix can capture who generates which information and who has access to it. By merging the state vectors of the minds of collaborating individuals plus their proprietary information in the state vector of a group, the model can be presented on an aggregation level that is appropriate for the current research. On this aggregation level the communication within the collaborating group becomes part of the self-affecting process presented on the diagonal of the transition matrix. Using these principles, an example of a non-collaborative development in the state space model is created. The example describes the following situation:

- Three design groups work on a non-collaborative system development. Two groups work in parallel, while the third group works sequential to the first two groups. The design group for which the proposed method is developed is called the target design group.
- Each design group is strictly non-collaborative with the other groups. The only communication of a design group with others is its final sub-system specification, which is only communicated to parties that need to work with it.
- Design teams make observations of the part of the domain of reality and stakeholders that they want to affect and use knowledge generated by others. The people that generate this knowledge are not shown in the model.
- Design teams affect the state of end users and other stakeholders only indirectly, through the state of the domain of reality that is affected by the implementers of the designs. The implementation is performed after the complete design is specified.
- People without a stake in the development are not shown in the model.

When sub state-vectors are arranged in an order that reflects the chronology in which they are first affected by the processes in the non-collaborative development (with arbitrary order for parallel processes), the following state space model is obtained:

\[
\begin{bmatrix}
B & A & B \\
\square & \square & \square \\
\square & B & \square & \square \\
B & \square & \square & \square \\
\end{bmatrix}
\begin{bmatrix}
\text{Public knowledge} \\
\text{Target design group} \\
\text{External design group 1} \\
\text{External design group 2} \\
\text{Implementers} \\
\text{Reality & stakeholders}
\end{bmatrix}
\]  

(3-8)

with:

\[A, B\] = sub matrix over which the target design group has (partial) control (internal processes and communication, respectively),

\[\square\] = sub matrix representing processes external to the target design group.
The chronology and the lack of collaboration yield a dominantly lower-triangular matrix. The upper triangle only contains observations made by the designers of the state of reality & stakeholders before it is affected by their activities.

Although the state space formulation is not specific for design situations, the selection of sub state-vectors and the identification of the pattern of sub matrices give it its designer’s perspective here. The generic nature of the model makes it suitable for representation of the relations between societal parts of the state vector and designerly parts. The connection between society and engineering in technology development, innovation and design is becoming stronger and more acknowledged, as observed by for instance Ropohl\textsuperscript{242} and Marxt and Hacklin\textsuperscript{196}. Since this research aims to support a design process in a societal development, it is considered essential to model its place in the societal environment. Therefore, the state space model is considered a suitable starting point thanks to, rather than despite, its lack of detail of the involved processes. The aim of this research calls for the focus on other design groups in the societal environment of the target design group. The perspective of the target design group is indicated by using A and B for the sub matrices over which this group has (partial) control. The A sub matrix indicates the changes within the domain of this design group and represents the internal design activities. The four B sub matrices indicate its communication, while the squares indicate all external processes, over which this group has no direct control. In this thesis the model in Equation (3-8) is used to characterise non-collaborative development from a design group’s perspective, although each development will have different nuances.

### 3.3 Purpose and principles of form and function

#### 3.3.1 Purpose and scope of the method

When the system development of Equation (3-8) is performed with collaboration, the representative state space model reduces to:

\[
\begin{bmatrix}
B & A & B \\
B & & \\
& & \\
\end{bmatrix}
\begin{pmatrix}
\text{Public knowledge} \\
\text{Collaborating design groups} \\
\text{Implementers} \\
\text{Reality & stakeholders} \\
\end{pmatrix}
\]  

(3-9)

The design group has no direct control over the state of implementers, reality and stakeholders. This is represented by the three squares for the external processes on the lower right-hand side of the matrix. This control is achieved indirectly by providing instructions for the implementers to make artefacts and by providing instructions to stakeholders for the use of the artefacts. If these instructions are complete and unambiguous, the actions of the implementers do not involve complex cognitive processes and can be anticipated by the designers. Note that in this model the implementation process is also designed by the design groups. The actions of the stakeholders can also be anticipated fairly well, although it is more challenging to anticipate their assessment of value. Comparing Equation (3-8) and Equation (3-9), several differences are observed. These differences and possible consequences are given in Table 3-2.
The purpose of the method presented in this theory is to minimise the consequences of the differences between collaborative design and non-collaborative development for the sub system for whose design the method is used, with minimal need to expand the design team with people with new expertise.

For the derivation of the principles of form and function and the principles of implementation, the scope of the method will not be restricted a priori. At this point the method is intended to be applicable to any design group in non-collaborative development where collaboration is undesirable or impracticable. There are also no a priori restrictions on the design phase for which it is intended to be used. However, the principles of implementation will reveal practical limitations that will be encountered during further development of instruments needed to apply the method. The consequences for the practical scope of applicability are briefly discussed in Section 3.5.1 and more extensively in Section 7.3.

<table>
<thead>
<tr>
<th>Observed difference</th>
<th>Possible consequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Each design group makes its own observations.</td>
<td>Different design groups have different images of the state of the world.</td>
</tr>
<tr>
<td>Each design group uses its own sub-set of public knowledge.</td>
<td>Each design group does not possess the complete and accurate causal model to anticipate the consequences for implementers, reality and stakeholders. Particularly, each design group has a focus on its own specific knowledge, leading to possibly misinformed anticipation of the effects of design choices of other design groups.</td>
</tr>
<tr>
<td>The system specifications are divided in sub-system specifications from different design groups.</td>
<td>Neither of the sub-sets contains sufficient information to fully anticipate the consequences for implementers, reality and stakeholders. The boundaries between the subdivisions are not fixed and clear.</td>
</tr>
<tr>
<td>From the perspective of one design group, the external processes include complex cognitive processes for which the outcome is not evident.</td>
<td>The magnitude of (indirect) control over the effect on the stakeholders is reduced. The consequences of the sub-system specifications for implementers, reality and stakeholders cannot be fully anticipated.</td>
</tr>
<tr>
<td>The three-by-three sub matrix of self-affecting processes of the states of the three design groups contains zero sub matrices (in the upper triangle), which could be non-zero in the collaborative design process matrix $A$ in Equation (3-9)</td>
<td>Design groups do not have full access to information of other design groups. Design methods that need such information cannot be used. The intermediate and final states of the design groups differ, meaning eventually that the design solution differs.</td>
</tr>
</tbody>
</table>

Table 3-2 Differences of non-collaborative development w.r.t. collaborative design and associated possible consequences
3.3.2 Principles of form and function

Differences between collaborative design and non-collaborative development

To obtain the principles of form and function from the main purpose of the method, the difference between a collaborative design process and the non-collaborative development from the perspective of the target design group is identified in the state-space model. First, the model of collaborative design is detailed by separation of the sub state-vector of the collaborating design groups into sub state-vectors of the individual design teams and a group of collaboration engineers. The latter group is assumed to perform the system level engineering activities. The number of sub-system design groups is kept the same as in Equation (3-8) for simplicity, but this does not affect the derivation of form and function. Finally, the sub matrices are identified that are new or changed in collaborative design with respect to non-collaborative development. These differences are shown in the following model:

\[
\begin{bmatrix}
\Delta^\ast & \Delta^\ast & B^\ast & \Delta^\ast & \Delta^\ast & \Delta^\ast & \Delta^\ast \\
B & B^* & \Delta A & B^* & B^* & B & B \\
\Delta^\circ & \Delta^\circ & B^* & \Delta^\circ & \Delta^\circ & \Delta^\circ & \Delta^\circ \\
\Delta^\circ & \Delta^\circ & \Delta B & \Delta^\circ & \Delta^\circ & \Delta^\circ & \Delta^\circ \\
\Delta B & \Delta^\circ & \Delta^\circ & \Delta^\circ & \Delta^\circ & \Delta^\circ & \Delta^\circ \\
\Delta^\circ & \Delta^\circ & \Delta^\circ & \Delta^\circ & \Delta^\circ & \Delta^\circ & \Delta^\circ \\
\end{bmatrix}
\]

(3-10)

with:

\(\Delta A\), \(\Delta B\) = changed design activity or communication of the target design group,

\(B^*\) = new communication of the target design group,

\(\Delta^\circ\) = changed design activity or communication of external groups,

\(\Delta^\ast\) = new design activity or communication of external groups.

For the following discussion it is noted that not all processes in Equation (3-10) change state-vectors during the design process and could be performed before or after the design process. This concerns the processes that are represented by matrices in the first and last column as well as those in the last two rows. Therefore, these sub matrices are greyed in Equation (3-10).

Software for design process emulation

To achieve the purpose of the method, it must make the design activities and communication of the target design group in the non-collaborative development to come as close as possible to what they would be in collaborative design. Therefore, the method entails the activities represented by the matrices associated with the target design group in the model. These activities are only possible when the activities of the external groups and associated sub state-vectors are also available within the method. These processes and state vectors require knowledge and expertise that is typically not
available in the target design group. Because the method intends to minimise the need to expand the design team, these processes should be implemented in software to the maximum extent possible. This implementation will be called the *emulation* of the external design processes and *collaboration engineering* and this constitutes the primary instrument for application of the method.

The $B$ sub matrices in Equation (3-10) interface between the target design group and the emulation. Considering the definition of the $B$ sub matrices in Equation (3-6), these represent processes that are partly related to one side of the communication and partly to the other side. The part that interfaces with the emulation in software requires a formal structure and language, suitable for computerisation. The other site of the communication can be implemented in any form suitable to the target design group. Because cross-domain communication tends to lead to misinterpretation\textsuperscript{196}, the output of the emulation should be in a form understandable for non-experts of the emulated domain.

The changes in the internal design process, the $\Delta A$ sub matrix, can be implemented in any form suitable to the target design group. As a guideline, the original form of existing activities can be maintained, but further automation of internal activities should be considered when the new information flows lead to or require frequent changes in the internal design state-vector. What should change in the internal design process can be described in instructions, particularly relating to the use of the emulation software.

These principles of form allow some slack for implementation of the external processes with human designers, instead of with software. By doing so, less of the goal to minimise the need of people with new expertise is achieved. This thesis focuses on implementation as emulation in software only. The idea of capturing abilities of other designers in software is formulated by Ropohl\textsuperscript{242} in the following way: “What has been transmitted by human communication before, is internalized now through the appropriation of artifacts. [...] Everybody who owns a pocket calculator is able to extract the square root of any number, even if he never has learnt the respective calculus.” The principal function of emulation is therefore to internalise abilities of other designers in the design process of the target design group. The functions of the software and its use are further detailed below.

**Functions of the software and its use**

The previous section identifies the main function of the method and the three building blocks of its instrumental realisation: software to emulate external processes, the *interface* between the emulation and the designers and guidelines for the inclusion of emulation in the internal design process. This division is based on form. This section considers a different subdivision of the activities in Equation (3-10) that provides a better basis to give an overview of the functions of the method. This division consists of three functional blocks, each relating to the activities associated to one of the following groups: the collaboration engineers, the target design group and the external design groups. For each of these three functional blocks the following functions are identified by consideration of the meaning of the $A$ and $B$ sub matrices that represent change or influence of the sub state-vectors of these groups:
Capture the necessary domain-specific knowledge (first column in Equation (3-10))
Observe the outside world for relevant information pertaining to the domain (last column in Equation (3-10))
Obtain information from the other groups
Effectively use the observations and information in design activities
Provide information to the other groups

For the emulation of collaborative engineering and the external design all these functions need to be addressed in the method. For the internal design only the activities that are changed with respect to the non-collaborative development need to be addressed. Some internal design activities in the non-collaborative development may become obsolete when emulation is implemented. For instance, strategic market analysis on the level of the subsystem to generate internal requirements may become less.

### 3.4 Principles of implementation and expository instantiation

#### 3.4.1 Implement a function or not?

It will be infeasible to emulate all activities of a collaborative design process, both because of restrictions in resources and because current knowledge is insufficient to achieve this. This can easily be argued: otherwise there would be little to stop replacement of designers by emulation and this is not observed in practice. Others have also deemed design as an endeavour that cannot be totally automated\(^4\). The previous section identifies the functions that need to be fulfilled to fully internalise collaborative design in the internal design process. During the implementation it needs to be decided if and how these functions are captured by the instantiation. Table 3-3 lists the three options and their consequences. These consequences need to be considered during implementation and are the cornerstone for the principles of implementation.

#### 3.4.2 Guidelines for the implementation procedure

There are many possible approaches for the design of the instantiation of the functions of Section 3.3.2. This section provides guidelines that can be supportive of this process, but these are not intended to be restrictive. Guidelines are given for the following procedures:

<table>
<thead>
<tr>
<th>Option to fulfil a function</th>
<th>Consequence for use of the instantiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Implement an emulation of a process that fulfils this function</td>
<td>Enables the intended use of the instantiation</td>
</tr>
<tr>
<td>Fulfil the function before implementation and capture the result in the instantiation</td>
<td>Enables the intended use of the instantiation, up to the point where the function is called again and the result is needed to change</td>
</tr>
<tr>
<td>Ignore the function</td>
<td>Reduces the scope of applicability</td>
</tr>
</tbody>
</table>

Table 3-3 Implementation options to fulfil a function and their consequence
• determination of application-specific functional specification
• reduction of scope of the functional specification
• determination of application-specific data and procedures
• generation of the emulation software

**Determination of application-specific functional specification**

For implementation of the instruments for the method for a specific design process, the functional specification needs to be more detailed than that given in Section 3.3.2. Analysing the procedure that leads to this general function specification reveals three steps that need to be taken first. One, analyse the non-collaborative development to identify the final system, the sub systems designed in external processes and the communication between internal design and external design processes. Two, select a collaborative design paradigm and fill this in for the identified system. Three, compare the two to identify the differences to be mitigated by the method. Although the selection of collaborative design paradigm could formally also be considered to be emulated, this would be incredibly demanding. Because the collective design paradigm is generally unchanged during a design process, it can be defined during the implementation of the instantiation, with limited risk to suffer from the consequence given for option two in Table 3-3. The more details are added to the collaborative design paradigm, the more detailed the functional specifications of the emulated processes and communication become. The state-space notation used in this thesis only provides a template for the initial descriptions, such as the definition of design groups. Further detailing of the collaborative design paradigm corresponds with determining the functions that are represented by the A and B sub matrices. This needs other forms of representation, such as verbal descriptions, work flow diagrams, communication protocols etc. It is recommended to start with a high level but complete description of the design paradigm and to make stepwise refinements of relevant parts jointly with the process of reduction of scope described next.

**Reduction of scope of the functional specification**

As stated in Section 3.4.1, it is currently not feasible to make an instantiation that meets the full functional requirements as would be obtained from the collaborative design paradigm. A reduction of the functional scope is therefore inevitable. There are two requirements for the reduced functional description: it must be feasible to make a corresponding instantiation and the instantiation must still be useful to the internal design process. To provide an impression of feasibility, several potential building blocks for the instantiation are provided in Section 3.4.3. This paragraph further considers reduction of functional scope in relation to utility.

Referring to Section 3.3, the primary condition for the method to have utility in the internal design process is that its use needs minimal extension of the expertise that is present in the internal design process. Figure 3-2 illustrates an arbitrary process diagram for collaborative design to identify and explain several principles for the reduction of scope. The dashed box outlines the reduced scope for the intended use of the instantiation. To enable autonomous use of the instantiation in the internal design process, the following principles apply to the reduction of scope:
▪ The inputs of the dashed box, which are the results (outputs) of upstream activities in the hatched boxes, need to be available in the instantiation
▪ All external activities occurring in a loop with the internal activities of the intended scope need to be emulated (chequered box)
▪ Activities that run in parallel with or downstream of the internal activities of the intended scope have no effect on the instantiation (dotted boxes)

A process diagram of the collaborative design paradigm can be used to identify groups of processes that comply with these principles, starting with the internal design activities that are desired to be supported and bearing in mind which external activities are feasible to emulate. The refinement of the process diagram for the scope of the instantiation can benefit from drafting use cases, which actually describe how the emulation is intended to be used\textsuperscript{67, 82, 247}. The reduction of scope is made easier when a design paradigm is selected that tries to minimise the recursive aspect of design. For instance, a division into phases of conceptual design, preliminary design and detailed design tries to instigate gradual refinement with minimal feedback to earlier phases. When the emulation tool is used during preliminary design, the results of conceptual design need to be available in the tool and the activities deployed during detailed design can be ignored. Only preliminary design activities need to be emulated. In practice, full compliance with the principles of reduction of scope may be difficult and for instance some weaker feedback loops are not considered (dotted line in Figure 3-2). Such instantiations may run out of their scope during the internal design process in which it is applied. Some consequences of this are discussed in Section 3.5.1.

\textit{Figure 3-2} Example process diagram for collaborative design with scope of the instantiation of the method
**Determination of application-specific data and procedures**

This part of the implementation relates to finding ways to perform the functions listed in Section 3.3.2. From the discussion of implementation up to this point three types of application-specific information are identified: content of a collaborative design paradigm, results of upstream design steps that are not emulated and emulation algorithms. The next paragraphs discuss how each of these types of information can be obtained.

For a non-collaborative development it can be expected that no application-specific collaborative design paradigm is available. The implementation of emulation of collaborative activities will usually need to be based on general knowledge about collaborative design and on the translation of collaborative design activities in other areas of application. This requires expertise in both collaborative design and the application domain.

Some intermediate design results that are fixed in the instantiation can be obtained from observations of the non-collaborative development. For instance, reverse engineering tools may be useful to obtain structural and functional breakdowns from typical design solutions. Results that cannot effectively be obtained this way, such as for instance the system level requirements, can be obtained by performing the necessary initial design processes that lead to these results. For this purpose, tools fitting the selected collaborative design paradigm can be used, such as for instance systems engineering tools. Depending on the type of result that is required, this may require designerly expertise in both collaborative design and the application domain.

Examples of tools that can be useful to perform the design activities that are not emulated are system breakdown structures, functional flow and breakdown diagrams and design structure matrices.

The implementation of the emulation of external design processes can build on knowledge of the associated design processes in non-collaborative development, because the sub matrices for the external processes in Equation (3-10) represent activities that have much in common with their counterpart in Equation (3-8). Observation of these design processes and corresponding literature will help to establish relevant information and design activities. Methods from knowledge based engineering can be suitable to translate knowledge from expert designers to formal descriptions suitable for design automation. Several methods exist to reduce the extent of the emulation, e.g. by reduction of the communication parameters between internal and external design processes, reduction of the external design problem, increase of efficiency of the emulated activities or replacement of design activities by heuristic knowledge.

**Generation of emulation software**

The main instrument that needs to be designed and implemented to apply the method is the emulation software. Therefore, methods from the field of information systems and software development can be helpful to organise the work and to formulate the structure of the software. An example of a possibly helpful instrument is a modelling language. The structure of the state-space model can help to generate the backbone structure or template of the software. For instance, an agent model can be based on the sub state-
vectors, with the self-changing and communicative processes as its methods\textsuperscript{54}. Logical splits and merges of sub state-vectors can identify hierarchical levels in the agent model in much the same way as used in Equations (3-6), (3-8) and (3-9). From observation of the state-space structure it is suggested to separate software elements that deal with processes in the world of material reality from software elements that also deal with externalised cognitive processes. The first are considered time-invariant, while the latter are continuously evolving. Further details in the software structure depend on the choices made for the functional description. Typical elements that can be expected are an object model of the system, inheritance of generic design activities by different instantiations of design agents and re-use of objects and procedures in different use cases.

### 3.4.3 Examples of building blocks for emulation

The principles discussed in the previous section particularly help to refine the functional specifications. However, the theory does not provide guidelines about how these functions can be performed by the instantiation. In many possible applications of this theory the amount of additional design theories that is required to achieve the implementation of emulation is substantial. Fortunately, much research has been conducted to develop methods for computational support of design processes. In some way all formulations of methods are a step in the direction of design automation, considering that methods formalise procedures and externalise design thinking\textsuperscript{72}. Many methods are described in general textbooks\textsuperscript{72, 231, 232, 241, 277}. The main distinguishing issue to be considered when reviewing such methods is that the current application in principle does not allow interaction with designers inside the activities that are emulated. This section gives a selection of building blocks provided by other research to enhance the understanding of the instantiation and to give a first impression of feasibilities. The blocks are selected for their potential to contribute to automation of design for emulation purposes. Building blocks for the changes in the internal design process and for the instructions of use of the emulation are not treated. The building blocks are not formally categorised, although they are presented in groups. However, they can be deployed in different ways.

### Data types, information structuring and relations

Design literature provides many suggestions to formalise design information, with or without the intention to store or use it in a computer. The terminology of design literature shows which data types are relevant. Besides data types commonly used to describe the material world, such as concepts, properties and behaviour, data types in design literature define how to express what is desirable, for instance as functionality, robustness, manufacturability and costs. Many models are developed to cope with and structure the large amount of information\textsuperscript{38, 98, 141}. Design theories and tools reveal the types of relations that can exist between such data, which are for instance hierarchical, chronological, logical or physical. Examples of tools that formalise relations suitable for a computerised template are breakdown structures, flow diagrams, aspect systems, Function-Quality Deployment and Design Structure Matrices. Part of research in Knowledge Based Engineering (KBE) is dedicated to identifying and formalising data types and relations. Besides methods to capture information of the content of a design process, there is also knowledge about capturing information about the process itself,
such as reasoning and back-tracking\textsuperscript{36, 215} and information about the organisation, such as work flow diagrams.

**Interfacing**

The B sub matrices in the state-space model can be considered to represent manipulation of information without the intention to change its meaning. Interfacing between the information used inside the instantiation and the user generally requires such manipulation. Interfacing with the user to capture design information as input or to represent design information as output has been researched in many contexts\textsuperscript{97, 126, 302}. Although in engineering there is an emphasis on representation of hardware, the representation of the combination of products and services or users is also researched\textsuperscript{134, 289}. The interfacing between the user and the emulation tool implies that the information from the tool is represented to a non-expert. Research on communication in collaborative design may help defining representations that do not lead to misinterpretation, as well as communication between the emulated design processes\textsuperscript{293}. Parsers extract and convert data to make output in one form suitable for input in another form and can be used for data conversion inside the emulation tool. For system design, the use of meta-models and high level primitives are researched as a means to structure data storage and conversion for the models of generated design solutions\textsuperscript{181, 272}.

**Simulation, judgement and iterative optimisation**

Much design research has been and is directed toward simulation of the behaviour of provisional design solutions. The research generally aims at adequate, yet sufficiently quick simulation under the various conditions that can be expected. Knowledge about simulation provides a basis for emulation. Another basis is provided by evaluation methods, which support judgement of the provisional solutions. Cost-estimation methods are recurring in many applications\textsuperscript{198, 203, 218}. When the objective of the design is not captured in a single parameter, there are methods for multi-criteria analysis\textsuperscript{214, 226, 229, 314} or qualitative information\textsuperscript{61}. Optimisation algorithms are a means to close the loop of synthesis-simulation-evaluation. There are algorithms for parameter optimisation\textsuperscript{70}, topology optimisation\textsuperscript{6} and configuration optimisation\textsuperscript{69}. For large and complex systems, multi-level optimisation algorithms are developed, such as Bi-Level integrated system synthesis (BLISS)\textsuperscript{255} and approaches to connect computation processes on different computers\textsuperscript{200}. Research on Multidisciplinary Design Optimisation (MDO) provides additional tools that can be used for simulation and optimisation, such as Design Engineering Engines\textsuperscript{292}. Various methods apply parametric variation in combination with simulation, evaluation and/or optimisation to obtain for instance statistical information, sensitivities, robustness evaluation or probabilistic optimisation\textsuperscript{63}. Although there is an emphasis on quantitative information in optimisation, methods are also developed to include qualitative information\textsuperscript{61}.

**Knowledge and heuristics**

Several KBE methods minimise or escape the iterative design cycle by heuristics, in the sense of rules of thumb developed by an expert as part of his/her expertise\textsuperscript{54, 204}. For instance, designers can use a smart sequence when fixing design variables or they can justly prefer certain design solutions over other solutions without needing a formal evaluation. KBE methods can capture and formalise such process and product
knowledge. As mentioned in Section 3.4.2, such methods may be helpful to determine application-specific procedures, but some knowledge is already formalised and available for implementation, for instance in the form of scaling rules. Highly heuristic methods consider the design activities and solutions as a black box and directly correlate a judgment to a requirement. For instance, cost modelling based on curve fitting of actual design solutions connects costs to a high level product specification, without specifying details of the design solutions. Some KBE methods use databases of sub solutions and their behaviour for bottom-up reasoning processes, such as morphological charts. Case based reasoning uses a database to search for solutions that perform the required function in a (potentially) different application21, 235. Some systems even adapt the selected solution to the new design requirements21. Knowledge and heuristic information is often needed to automate creative processes. Several tools exist for the synthesis of solutions57, 58, 235, 265. The combination of artificial intelligence (AI) for creative processes with numerical optimisation is also researched52. Karni and Arciszewski168 provide a list of knowledge operators that can be used as templates for design activities.

**Design for X**

Design For X (DFX) methods focus on a specific aspect, ‘X’, of the design solution. Some of these methods focus on a specific property of the design solution, such as design for reliability or design for robustness15, 85, 254. In other methods, ‘X’ stands for a downstream process, such as manufacturing, assembly or installation129, 308. Such methods need to make an assessment of how the design solution will affect design of these processes. DFX methods that do not include cooperation with the designers of these downstream processes use other means in order to make the assessment, such as modelling of producibility rules104 or automatic exploration of feasible disassembly sequences56. Design for availability involves both complex properties of the system such as reliability and downstream processes such as corrective maintenance. Tools to design for availability are particularly relevant due to the increasing complexity of modern engineering systems275.

### 3.5 Other components of the design theory

#### 3.5.1 Artefact mutability and practical scope

The artefact of this theory consists of the three building blocks identified in Section 3.3.2: software to emulate external processes, instructions to change the internal design process and the interface between the emulation tool and the designers. The artefact is subject to two levels of variability. First, when in use in a design process, it will pass through different system states. This variability forms the behaviour of the artefact needed to perform its intended function. Second, the artefact can be modified through redesign, by changes to the software code or instruction. This section only addresses the second type of mutability.

Although the purpose and principle of form and function take full emulation of collaborative design and external design as the starting point for implementation, Section 3.4 shows that choices need to be made during the implementation process that
inevitably lead to a reduction in functionality of the instantiation and possibly to unintended behaviour. The following types of choices are identified:

1. software engineering choices, such as language, platform and data structure
2. information system choices, such as functional flows and formalisations
3. design approach choices, such as design paradigm and methods
4. design content choices, such as fixed concepts for the externally designed sub systems

Each of the choices is governed by prioritisation of needs, availability of knowledge and availability of resources. For an initial instantiation the choices made determine its practical scope of application. The most critical aspect for this practical scope is expected to be the feasibility of implementation of the emulation in an information system. Therefore, the building blocks presented in Section 3.4.3 belong to where research on information systems and research on design meet. Although no full literature review on this topic is performed, it is observed in general terms that knowledge about computerisation of rational methods is more progressed than that about creative methods (terminology according to Cross72). Within the rational methods largest successes are seen for dimensioning (e.g. numerical optimisation), followed by configuration variation (e.g. Design Engineering Engines292, Quaestor290, genetic optimisation) and mapping from function to structure (e.g. case based reasoning), using both iterative and heuristic approaches. The more system elements and the more disciplines involved, the more challenging implementation becomes.

Before or during application of the instantiation in a design process, the desire to improve the functionality, validity or effectiveness can be initiated by a change in the needs, knowledge or resources. This leads the makers of the instantiation back to the choices that were categorised above. The top-down order of the types of choices in the list can in general be associated with a ranking for various properties that relate to mutability in the following ways:

- from generic to application specific
- from difficult to change to easy to change
- from long-term to short-term changes in knowledge
- from long-term to short-term changes in needs

This implies the fortunate situation that those aspects that initiate change most frequently are also easiest to address in the instantiation. The more difficult changes relating to the first three types of choices are not expected to be required during the execution of a design process. Therefore, these changes will mostly be done in regular upgrading of the tool. However, the scope of the design content may be exceeded during use of the tool, when the designer wants to revisit the design content choices made during implementation. Therefore, it will be most challenging to accommodate such desired changes under the time constraints of the on-going design process.

### 3.5.2 Testable propositions

The purpose and principles of form and function, as formulated in Section 3.3, imply the following 2 axioms:
1. Sub systems designed in a collaborative process are better than sub systems that are designed without collaboration
2. Sub systems designed with perfect emulation of the non-present processes of collaborative design are equal to sub systems designed with collaboration

The second axiom, which is the more distinguishing of the two for this theory, cannot be tested directly. The practical scope of instantiations is limited, as discussed in Section 3.5.1, and the test will be influenced by imperfections. There are many sources for imperfections in a test, such as

- lack of reference for the collaborative design paradigm
- improper reduction of scope
- use of incorrect complementary theories to address the functions
- improper design of the instantiation
- improper use of the tools during the test, e.g. due to lack of experience\textsuperscript{133}

Testable propositions need to be derived from the axioms and the reduction of scope and need to provide guidelines for the interpretation of the results acknowledging the imperfections. These can only be formulated when the instantiation and test conditions are defined. Experiments for similar methods may serve as a model for the setup of a test\textsuperscript{243}.

The necessity of reduction of scope and the inevitability of imperfections leads to a third axiom that needs to be validated to grant the theory merit:

3. There exists an application for which the use of emulation of the external design processes based on the guidelines of this theory provides utility, despite its reduction of scope and imperfections

There is no test to falsify this axiom, but it can be confirmed by any successful application.
“A major difficulty in the design of economic offshore farms is the interaction between the components.”
Cockerill, 2005

4 Offshore wind turbine optimisation with farm design emulation tool

4.1 Purpose and methods of designing the expository instantiation

4.1.1 Introduction
The previous chapter develops the theoretical framework for the improvement of subsystem design in a non-collaborative paradigm. The original motivation to develop this theory came from the desire to improve the design of wind turbines for application in offshore wind farms. This chapter describes the development of an expository instantiation of the theory, aiming at the support of offshore wind turbine design. The purpose of this practical implementation is to test the validity of the design theory. This validation itself is presented in Chapter 6.

The development of the practical implementation will follow the principles that are described in the design theory of Chapter 3. This means first of all that the product of this development will be a software tool and recommendations for its use. The software will emulate the external wind farm design processes and by using the tool collaboration between the RNA designer and the external wind farm designers will be mimicked. Since the guidelines of Chapter 3 are formulated in generic, abstract terms, domain specific knowledge of offshore wind energy needs to be used to translate them to a practical implementation. Furthermore, the design theory provides only guidelines for certain aspects of the development. Therefore, other design theories are needed as well. Most of these theories, as well as the knowledge about offshore wind energy, are discussed in the sections where they are relevant. It is noted in the guidelines for implementation, in Section 3.4.2, that methods from the field of information systems and software development can be helpful to organise the work, because the main artefact that needs to be designed is the emulation software. Therefore, theories about organising software design are discussed first. This will lead to the chosen process for the development of the software.
Software development life cycle models, describe various different design processes for software. Which design methods are most effective depends on the role the software will play. Since the software will be used to validate the theory, its role is similar to that of a wind turbine model in a wind tunnel for aerodynamic research. It is not the real thing, to be used in a commercial application. Rather, it is a prototype, with the purpose to generate knowledge. According to Tate virtually all software development as part of a research project is, or has the characteristics of, a prototype. This role of the software is emphasised here, since prototypes of software are often misunderstood to be the real system.

Several types of prototyping are encountered in software development. Davis et al. and Tate identify the following two types: throwaway prototyping and revolutionary prototyping. The term ‘rapid prototyping’ is also frequently used, but this doesn’t classify a specific type of prototyping, since some degree of speed is implied in almost all cases. Revolutionary prototyping starts with those system aspects and user needs that are best understood. The resulting prototype “may grow and change into something that eventually becomes part of the real system.” On the contrary, throwaway prototyping is likely to implement only those aspects of the system that are poorly understood. The prototype that will be constructed in this research intends to test the as yet unknown usefulness of design emulation. Furthermore, it will help understand how well user needs are met with this type of tool. This role of the prototype matches best with throwaway prototyping. Possibly, the life cycle of this throwaway prototype ends at the end of this research project. However, throwaway prototypes may also “continue for a time to be useful for some purposes, but not as part of the real system.” Extension of the lifetime of the prototype beyond the duration of this research is not considered as a requirement for the development.

Creating a prototype gives some liberty, since only certain aspects of the system need to be implemented. This relaxes the requirements and reduces the scope of the design. The requirements of the prototype will be driven by its short lived use in the validation activity and not by industrial needs. Further developments that are needed before the tool can be applied in a practical situation are assessed in Section 7.2, where the contextualisation is discussed.

The development of a throwaway prototype is often not described as a stand-alone activity, but rather as a method in a larger system development. The software development life cycle models typically address the development of this larger system, with limited guidelines for the actual activity of creating the prototype. However, since the prototype is also a software system in itself, the suitability of guidelines for the larger system development is nevertheless assessed for the prototype development. Alexander and Davis define three levels of abstraction in software development models, numbering them 3, 2 and 1 from the top level to the bottom level. At the top level, level 3, groups of activities are defined. At level 2, the activities are refined and ordered in process models. Level 1 shows the tools and techniques used to perform the activities. These three levels are used to select and clarify the development approach. The next three sections treat the choices made for the approach on each level, from top to bottom. Once the design process is clarified, the further layout of this chapter is explained in Section 4.1.5.
It is recognised that more and more recent models for software engineering exist than the ones that are reviewed in this section. However, for this relatively small scale development the used sources are assumed to be sufficiently representative and to lead to an effective approach. The strength of modern models in dealing with large and complex developments is not needed in this project.

4.1.2 Top level design model: Groups of activities

At the top level, broad groups of activities are delineated. Alexander and Davis⁹ provide an incomplete list of the following 5 top level process models:

- conventional
- incremental
- evolutionary
- operational prototyping
- concurrent software modelling

The first three models share three basic groups of activities: 1. Determine problem; 2. Develop; 3. Operate and Maintain. Whether or not these basic groups are shared with the last two models is not elaborated in the article. The first three models differ in how these groups of activities address subsets of the development problem. This is illustrated in Figure 4-1.

To select the most suitable top level process model, Alexander and Davis provide a list of 20 criteria, divided in five groups: personnel, problem, product, resource and organisation. Each of the previous three models can be scored, by judging the overlap of its strengths in these criteria with the needs of the project. The maximum score that can be achieved is 20. An analysis of the prototype development project against these

<table>
<thead>
<tr>
<th>Top level model</th>
<th>Basic group of activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>Determine problem: Entire problem set and product at once</td>
</tr>
<tr>
<td>Incremental</td>
<td>Develop: Problem subset 1 and product 1</td>
</tr>
<tr>
<td></td>
<td>All problem subsets at once</td>
</tr>
<tr>
<td></td>
<td>Problem subset 2 and product 2</td>
</tr>
<tr>
<td></td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>Operate and maintain: Problem subset N and target product</td>
</tr>
<tr>
<td>Evolutionary</td>
<td>Problem subset 1 and product 1</td>
</tr>
<tr>
<td></td>
<td>Problem subset 2 and product 2</td>
</tr>
<tr>
<td></td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>Problem subset N and target product</td>
</tr>
</tbody>
</table>

Figure 4-1 Three top level models for software development after Alexander and Davis⁹; Sub-products in the incremental and evolutionary model are operated but not maintained
criteria yielded the following scores:

- The conventional model scores 4/20
- The incremental model scores 7/20
- The evolutionary model scores 14/20

The largest difference in the scores comes from the match between the model and project on the problem criteria. The second contribution to the difference comes from the personnel criteria. The inexperience of both users and developers with this application domain, as well as the novelty of the problem, leads to the high score of the evolutionary model. Since the scores are wide apart and correspond with the intuitive assessment of the models by the author, the evolutionary model is selected for the development approach. Because this model describes three types of activities at level 2, choices have to be made about how to determine the problem, how to develop the product and how to operate and maintain it. This is done in the next section.

4.1.3 Second level design model: Activities

**Determine the problem for each of the problem subsets**

To determine the problem subsets, the needs of the user need to be assessed and an analysis needs to be made of how software can help to fulfil these. This is done in abstract terms in Chapter 3, to develop the design theory, and therefore the implementation guidelines that are formulated in Section 3.4 should be helpful to perform these activities for the particular situation of offshore wind turbine optimisation. The following three guidelines relating to the problem assessment were given:

- determination of application-specific functional specification
- reduction of scope of the functional description
- determination of application-specific data and procedures to implement

Chapter 3 shows that an analysis of the existing non-collaborative development helps to identify the internal and external design processes. This analysis also helps to define the boundary and communication between internal and external design groups, which is a starting point for the functional specification of the tool.

The function of the tool is to compensate for the lack of collaboration by emulation of collaborative design. Therefore, the first guideline requires the definition of a collaborative design model for the development of offshore wind farms that can be emulated. As discussed in Section 3.4.2, this is best addressed simultaneously with the reduction of the scope of the tool. Therefore, the first two guidelines define the first problem subset.

The third guideline asks for more detailed analysis of the design processes that are involved in offshore wind energy deployment. In current practice, it can be observed that some of these design processes are performed in more or less isolation of other design activities. This indicates that this part of the problem analysis, and its consecutive product development, can be further separated in problem subsets. As an
example, it might appear to be possible to separate the problem analysis and implementation of the design of support structures from the design of the electrical infrastructure. Therefore, the determination of the separability of offshore wind farm design is treated as a problem subset, followed by a problem subset for each of the isolated design activities that need to be emulated.

The interfacing with the user and with the file system are two additional separated problem subsets. Because these relate only remotely to the application domain, they are not treated in this dissertation.

**Develop the product**

As for the top level model selection, Alexander and Davis\(^9\) provide selection guidelines for several level 2 development processes. The following three processes are included in the selection: The waterfall model, hybrid prototyping and operational specification. The maximum score that each of the models can achieve is 16, instead of 20, since some of the criteria are not relevant and thus not scored in this evaluation. An analysis of the prototype development project yielded the following scores:

- The waterfall model scores 3/16
- Hybrid prototyping scores 9/16
- Operational specification scores 2/16

Operational specification scores poorly. This approach starts with specifying the external behaviour of a solution, rather than with the content of the software. It is therefore more suited for simple problems and solutions, of which experienced users and developers know clearly what is desired and how this can be implemented.

The waterfall model and hybrid prototyping have very similar activities, but differ in the sequence in which these are performed. Figure 4-2 shows these two models. In the waterfall model, the activities are performed in sequence, allowing for iterations of two consecutive phases. Each phase uses internal validation or testing, but the actual code is only generated near the end. In hybrid prototyping, one or more prototypes of the software live throughout all development phases and provide continuous feedback. The term ‘prototype’ may be confusing in the current context, since it doesn’t refer to the ‘prototype’ that is the eventual product of the current development. The prototypes in the hybrid prototyping model are best considered as sub-prototypes. Successful parts of the sub-prototypes are eventually used in the final code, which is tested at the end of the sequence.

The hybrid prototyping process provides much opportunity to learn and adapt during the development of the software product. This matches well with the novelty of the software that is developed. The hybrid prototyping process is therefore applied to each of the problem subsets in the evolutionary model.
Operate and maintain the product

The prototype will not be operated in the common sense of the word. Rather, it will be deployed in the validation program. This deployment, including its procedures, tools and techniques, is treated in Chapter 6. As mentioned in Section 4.1.1, the life cycle of the prototype may end at the end of this research project and therefore maintenance is not considered.

4.1.4 Lowest level design model: Tools and techniques

At the lowest level, tools, techniques and methods are chosen to perform the development activities. The set of such tools, techniques and methods can be called the development infrastructure. According to Wasserman\textsuperscript{303} “different types of software need differing degrees of development infrastructure”. Wasserman distinguishes ‘Controlled development’ and ‘Rapid application development (RAD)’, where he considers the latter to be appropriate for single user, single platform, low risk applications, built by one or two individuals. The current prototype development falls in this category. Wasserman states that “the tools for such a project may be no more than a text editor, a drawing tool, and either a programming environment, a RAD tool, or even a personal productivity tool”. Therefore, the selection of tools has not always been done in a rigorous fashion. This section discusses and states the choices that have been made.
As mentioned in Section 4.1.1, some degree of speed is implied in almost all cases of prototyping. Therefore, many authors stipulate the benefit of code reuse and, to a lesser extent, automated code generation. The use of code generation from Unified Modelling Language (UML) class diagrams, which is not domain specific, has been tested with Software Ideas Modeler. However, this was found to be ineffective in this case. Integrating automatically generated code for classes in the continuously changing sub-prototypes was more time consuming than editing the code directly. In general, reuse of software and code generation for a specific problem is more difficult than for generic applications and this narrows down the situations in which these paradigms can be used. Because offshore wind farm design emulation is a very specific application, no attempt has been made to find reusable code or automatic code generation for this part of the development. However, libraries for numerical optimisation are more widespread and it is highly desirable to reuse such code.

High level programming languages inherently incorporate code reuse and generation, particularly for common functions, such as mathematical operations. A high level language is thus a logical choice to make the prototype. To select the programming language, a list of languages is evaluated against a list of criteria. The scores on the criteria are provided by AwareTek and Lawlis, where weights can be set to specify the importance of the criteria for the project. Criteria that are deemed important in this case are:

- power and expressiveness
- ease of using the language
- ease of learning the language
- availability of compiler or interpreter (within the organisation)
- availability of third-party libraries
- efficiency (speed)
- quality of available tools
- possibilities for learning the language (tutorials, documentation, user-groups, etc.)

Out of 28 languages 13 languages are discarded in a pre-selection, based on qualitative arguments. For the following languages additional information and a score on the criteria are collected: Python, JavaScript, Visual Basic, Java, C++, C#, Ada95 (Ada 2005), Smalltalk, PHP, Lisp, Scheme, FORTRAN, C, Perl, Ruby. The highest score is obtained by Python. As a scripting language, it has a very short development cycle, suited for the dynamic prototyping activities. It facilitates ad-hoc programming without type declaration. It is expressive, class-based with a strong object model. It is easy to learn and use, has a huge library and an active community of users. However, the quality of third-party libraries is not always up to par and the processing speed is lower than that of most of the other languages. Although processing speed is important to minimise the time demanded of testers of the tool, this drawback is accepted. It is expected that careful selection of models and algorithms is a more dominant factor in processing speed than the speed of the interpreter. Most libraries that will be needed in the project are available in the distribution package of Python. In addition the often used libraries NumPy and SciPy (for scientific computing) are imported. All these libraries are expected to have acceptable quality.
There are several software development kits (SDK) for Python to create graphical user interfaces (GUI). For some of these SDKs visual code generation tools exist that help building the GUI. In turn, some of these visual tools operate as part of an integrated development environment (IDE). The dependency between these three development tools makes their selection intertwined. Shortlists are made containing 5 GUI SDKs, 13 visual GUI builders and 6 IDEs. These shortlists are subjected to a qualitative analysis and some tools are tested. Here it became apparent that the quality of third-party tools for Python does not always meet the desires. The options are further reduced by the restricted combinations that are possible for the three types of tools. Eventually, TKinter is selected as GUI SDK, without a visual builder. As integrated development environment (IDE) Eclipse is chosen. The plugin PyDev (Python development environment) is used to provide language specific support in the Eclipse environment. Versioning and revision control of the software is performed with Apache Subversion (svn), using the Subclipse plugin to work with svn from the IDE.

The use of UML diagrams to develop and represent the structure of the software is tested with VP-UML, but is judged to be ineffective in this case. Many UML diagrams are beyond the need for a small development and it is time consuming to keep up with the continuous changes in the hybrid prototyping approach. Since there is no immediate prospect of maintaining the code or transferring it to a third party, the effort to represent the software in UML is abandoned.

4.1.5 Layout of the report of the design process
Section 4.1.2 reports that the evolutionary model is chosen for the development of the tool and that in this model the activities are performed per problem subset. The layout of this chapter follows this separation of the development and presents the design of the tool per problem subset. Section 4.1.3 identifies the following problem subsets:

1. analysis of the non-collaborative development in practice
2. definition of a collaborative design paradigm and reduction of the scope of the tool
3. separation of offshore wind farm design in disciplinary design contributions
4. establish disciplinary design algorithms

The next four sections treat these four problem subsets sequentially. The section on the second problem subset includes a description of several possibilities for the use of the tool. The section on the disciplinary design algorithms starts with a generic analysis of this problem that is shared by all the disciplines.

The 3rd and 4th problem subsets include the selection of models to analyse and evaluate the designs of offshore wind farms. However, these models are presented separately to keep the discussions of the problem subsets focussed on the design aspects. The presentation of models is separated in a section on cost models and a section on physical models. Cost models are presented in Section 4.6. Because the underlying processes that they model are very time-variant, these models need frequent updating. Grouping them facilitates the assessment of which models are outdated, both in this document and in the source code. Physical models are presented in Section 4.7. These models are representations of the physical world. Therefore, they have a different nature than the
design models and the cost models, which each model expressions of the domain of the mind. The models of the physical world are assumed to model phenomena that are inherently time-invariant, although the models themselves could be updated with more precise models.

For each of the problem subsets, the approach consists of several activities, being: determine the problem, develop the product and operate and maintain the product. The development of the product is shown in Section 4.1.3 to consist of five functional blocks for hybrid prototyping: prototyping, requirements, design, code and test. All sections focus on the problem, the requirements and the design of the tool. The prototyping iterations and the coding activity are not discussed. The testing activity is treated in the last section of this chapter for the physical models, in the next chapter for the optimisation algorithms and in Chapter 6 for the utility of the chosen collaborative design paradigm. As mentioned in Section 4.1.3, operation of the tool is also treated in Chapter 6.

4.2 Analysis of the non-collaborative development activities

4.2.1 Introduction

This section analyses how offshore wind farms currently come about and in which sense collaboration is missing in this process. The purpose of this analysis is to identify the design process that is to be supported and which design processes need to be emulated by the tool. In terms of the constructs of the design theory of Appendix A, this section establishes the target design group, the internal and external design processes and the communication between these two.

4.2.2 System of interest

First the system of interest and its boundaries are explored. The starting point is the wind turbine that is designed for application in an offshore wind farm. The boundary of the system of interest should include all the turbines of this type that are produced and used. It can be observed in practice that wind turbines designed for offshore application are sometimes used onshore or have variants that are suited for onshore applications. The suitability of offshore turbines for onshore applications is expected to be less relevant for current and future multi-megawatt turbines or a spin-off with limited influence on their design. Therefore, onshore applications are considered to be outside the system of interest and the turbines are assumed to be designed for offshore applications only. The turbines are used in several offshore wind farms, so the system of interest at least encompasses turbines in more than one wind farm. The further extent of the system is comprised of two groups of items:

- items needed to complete the implementation and operation of these wind farms
- items in the pre-existing environment that affect or are affected by the wind farms

The first items form a clear-cut group that can be observed from offshore wind farms that have been built to date. These items are in first instance ‘actions’ that convert matter, energy or information (Zamora Guevara\textsuperscript{317} referring to Ullman\textsuperscript{276}). However, it is more convenient to express some of these actions in terms of the hardware they yield.
Hardware and procedures are collected through analysis of existing wind farms and of lists that were created in other projects. The extensive list of Herman\(^{139}\) is used as starting point and this is checked against and completed with information from many other sources\(^{4, 49, 105, 111, 178, 192, 202, 219}\).

For the second items, the word ‘environment’ needs to be interpreted in its widest sense to contain dead matter, including existing artefacts, and organisms, including people. The effect on and from people can be direct, but also indirect via the institutions in which people operate. The extent of the items that affect or are affected by the wind farms is not well defined. Considering the ‘butterfly effect’, the reach of the effect of wind farms can be enormous. This group of items is limited as much as possible, without jeopardising the validation power of the instantiation. The items are similarly collected from observations of existing wind farm developments and from literature.

The items that are collected to describe the system of interest are not reported comprehensively, because they form very large lists. Nevertheless, they are used throughout the development of the tool to check completeness and consistency. Therefore, many of the items on the lists appear in the further discussions of the tool development.

### 4.2.3 Involved design groups and their collaboration

The design activities leading up to the hardware and processes of the system of interest are executed by various groups that are divided over different companies. Mast\(^{197}\) investigated the roles of stakeholders in offshore wind energy. Several of these roles can be identified as suppliers or service providers that perform the design activities. These roles are denoted in Figure 4-3.

For the development and implementation of individual wind farms, several legal structures for collaboration are observed in practice. Kleineidam and Kaiser and Snyder identify general contracting (or: Engineering, Procure, Construct (EPC)), multi-contracting and working in a consortium\(^{166, 174}\). These legal frameworks influence the intensity of the collaboration between the design groups. However, the differences between the contractual frameworks are mostly discussed in terms of division of risks and management of physical interfaces. This indicates implicitly, that the nature of the collaborative activities is not one of extensive system level optimisation. Although this collaboration is not investigated in detail, several observations can be made that confirm restrictions to system level optimisation in current practices.

In all existing and planned offshore wind farms, the wind turbine is selected from the existing product portfolios of the manufacturers. Some modification can be implemented, for instance to better interface with transport and installation processes. As regards the design collaboration, this means that there is virtually no direct iterative optimisation of the turbines. The first level of assurance that the wind turbines meet the constraints of their application at sea is provided by its type certification. Design standards for offshore wind turbines allow turbines to be designed according to generic conditions, rather than site specific conditions\(^{86, 120, 153}\). During the development of a wind farm the suitability of the turbine is checked for the specific conditions that apply in that project. Several other elements that are designed specifically for each wind farm...
require information about the turbine’s properties or behaviour. For instance, its loading is needed to design the support structures, its geometry is needed to select installation equipment and its electrical output needs to be characterised to design the electrical infrastructure. This indicates that the collaboration between wind turbine designers and the other design groups is mostly one-way traffic of information. The practical execution of the communication is a little more complicated, because some of the turbine information is confidential. However, this doesn’t alter that the purpose of the communication is to assist the design processes of the other elements and not that of the turbine.

Similar restriction can be seen in several other design processes. For instance, electrical cables, switch gear and transformers are largely standardised solutions, with limited variability. Offshore equipment for foundation installation, turbine installation, cable laying and personnel access is normally selected from existing solutions. As for the wind turbines, the use of existing tools and more-or-less standard components is often preferred for the economy of scale this brings along. Despite the restriction on system level optimisation, this may therefore still be the most economic, and thus optimal, solution.

The analysis so far focuses on the development of a single wind farm. As derived earlier, the system of interest is larger than just one wind farm. In the framework of multiple wind farm developments over a longer period of time, there is little formal design collaboration. However, there is ample communication by means of conferences, articles, etc. Furthermore, many lessons are learned from observations of earlier wind farms, turbines, installation processes etc. Often, such information finds its way into
product improvements through the requirements. The larger framework of the system of interest provides opportunities to expand the list of standard solutions with new products. This implies that the system of interest is not limited to currently existing standard solutions.

4.2.4 Boundary between internal and external design

As implied by the previous discussion, wind turbine manufacturers have two roles in the development of offshore wind farms. First, they design the wind turbine for which they get a type certificate and create production facilities. Second, they design the modification to the turbine and aid the other design processes during a wind farm development. The first and by far largest design activity doesn’t have the advantages of design collaboration and is therefore a suitable candidate to validate the theory. This will therefore be the internal design process for which the prototype will be made. The boundary will be defined by:

The internal design process constitutes all design activities that lead to specifications of the wind turbine that are consistent in all applications of that wind turbine.

There are many situations in reality that may require a more nuanced definition. For instance, the same nacelle may be equipped with generators of various suppliers and blades of different length. Within the scope of the project it is expected that such nuances can be ignored. For the purpose of this research the definition will be used in a rather intuitive sense. The elements of the system of interest that are interpreted to be designed in the internal design process are identified from the collected items that are discussed in Section 4.2.2. Concerning hardware, the rotor-nacelle assembly is designed in the internal process. Tower design is considered to be part of the external design process. Towers vary too much between different wind farms, because they are optimised for the site specific conditions for which they have to be certified. Concerning procedures, the internal process designs the manufacturing of hardware, the repair actions, the service actions and the service intervals. The repair and service action designs do not include the design of logistics and crew deployment, since these vary for different farm sizes and locations. They focus on the necessary preparations on shore and on the activities per repair or service action once the crew is at the turbine.

As ascertained in the previous section, the communication between the internal and external design groups consists of providing information about wind turbine properties and behaviour to the external designers. Inputs to the internal design process are the informal communications and the observations of earlier wind farms, turbines, installation processes etc. Much of these inputs actually predate the design process and can be considered to be part of the knowledge base of the internal design group.

4.3 Emulation of collaboration for offshore wind energy

4.3.1 Introduction

The previous section illustrates how wind farms come about in reality. In this section, a hypothetical high level design paradigm is formulated, that will be the basis for the emulation of a collaborative design approach. There is no reference for this paradigm in
reality, since it describes a collaborative way of working that doesn’t exist. This provides much freedom when formulating the paradigm. However, Section 3.4.2 provides several guidelines. First, a high level formulation of the design paradigm is made, that illustrates the overall design life cycle. Using this high level formulation, the scope of the instantiation is selected. This leads to the high level functional specification of the prototype tool and its use.

4.3.2 Definition of the emulated collaborative design paradigm

One of the guidelines of Chapter 3 is that the reduction of scope is made easier when a design paradigm is selected that tries to minimise the recursive aspect of design. The waterfall paradigm that is shown for software design in Figure 4-2 has this characteristic. This paradigm is characterised by a sequence of stages in which the output of each stage becomes the input for the next. Although the process could return to earlier stages, as indicated by the feedback loops, there is an intention to minimise this. The design paradigm that is defined is therefore based on this waterfall paradigm. Because the waterfall paradigm in Figure 4-2 is defined for software engineering, ideas and terms of the basic design life cycle of Roozenburg and Eekels241 are used to translate this paradigm to the engineering design situation for wind energy systems. The best chance of successful emulation is expected for preliminary external design phases, because this implies a lower requirement on optimality and feasibility of the solutions. Therefore, the preliminary design phase is expanded, using descriptions of configuration design, architecture design and system level hardware design as referred to in that section. Furthermore, this design phase is expanded with details of the design of procedures to realise, operate and maintain the hardware. This expansion is made to include the process domain according to Suh262. Considering the preliminary design phase to be the most likely candidate for the scope of the instantiation, the other phases of the paradigm need less focus. Their sequencing may even be inadequately represented by the diagram, as long as the interactions with the phases inside the scope of the instantiation are correct. The last three activities in the waterfall paradigm, from coding to maintaining the software, are compressed, because these are outside the initial design activities of the life cycle. The resulting diagram for the paradigm is shown in Figure 4-4, indicating the search area for the scope of the instantiation.

It is expected that emulation of dimensioning and parametric optimisation for the external design process is more feasible than emulation of the more creative activities, such as core concept or configuration selection. However, this doesn’t restrict use of the tool to the same activity in the internal design process. To clarify this, the activities of interest in the design paradigm are separated into those in the internal design process, those in the external design process and those in the collaboration engineering process. This is shown in Figure 4-5. Data flow between the processes is not shown in this figure. The grey area indicates the targeted scope for the instantiation. The emulation by the tool covers the activities of the external process and the collaboration engineering process in this box. The activities of the internal design within the scope of the instantiation describe the use of the tool. The tool is not expected to be restricted to be useful for these activities only, but rather the use in these activities is expected to demonstrate the value of the tool. Offshore wind energy deployment is relatively young and at the beginning of the learning curve for various components and combinations of components165. Because of this phase of development, there is much interest in and
expectation of optimisation of concept and main dimensions of the wind turbine. The chosen scope of the instantiation is therefore expected to be both feasible and useful.

The scope of the instantiation in Figure 4-5 shows which design results of previous processes are assumed to be known and fixed before application of the tool. These are the requirements and the concept and configuration that come out of the external and collaboration processes. The scope of the instantiation for the external and collaboration processes shows which activities and communication need to be implemented in the tool. These are the parametric optimisations of the external hardware and procedures, using the analysis and evaluation in the external and collaboration processes. The final outcome of the internal processes in which the tool is used is the choice of the wind turbine concept, configuration and dimensions. Within the scope of the instantiation, there are several internal processes with internal feedback that are not further discussed. These are the parts of the shown activities that are also used in the non-collaborative approach and these are known to the wind turbine designers. The remaining parts inside the scope of the instantiation represent the use of the tool. They consist of the user activities and the communication between the user and the tool.

4.3.3 Functional specification of the tool and use cases
The use of the tool is expressed in use cases, as suggested in Section 3.4.2. The interaction between the user and the tool is one of collaborative optimisation of the dimensions and procedures of both the wind turbine and the other wind farm elements.
Since there is a separation between the design variables of the internal design process and those of the external process, this is per definition a case of multidisciplinary optimisation. The parameters that can independently be assigned a value in the optimisation process can be arranged in a design vector, $\mathbf{x}$. In multidisciplinary design optimisation, this vector is divided in a (possibly empty) sub vector $\mathbf{y}$ with linking variables, and several sub vectors $\mathbf{x}_j$ with local variables associated with discipline $j$.

The general formulation of this type of optimisation problem is given by Tosserams et al.:

$$\min_{y, x_1, \ldots, x_M} f(y, x_1, \ldots, x_M)$$

subject to:

$$g_j(y, x_1, \ldots, x_M) \leq 0 \quad j = 0, \ldots, M$$

$$h_j(y, x_1, \ldots, x_M) = 0 \quad j = 0, \ldots, M$$

in which $f$ is the objective function that needs to be minimised, $g_j$ are inequality constraints and $h_j$ are equality constraints. The sub vectors that are mentioned below ‘min’ denote which sub vectors are varied in the minimisation of the objective function. This notation differs from several others, in which the sub vectors in the objective function denote which variables are varied.

In the current analyses, the design vector is separated in two parts: A vector containing the design variables of the rotor-nacelle assembly and a vector containing the other design variables of the wind farms. The first vector will be indexed $i$ for ‘internal’, because it is associated with the design process of the wind turbine designer. The second vector will be indexed $e$ for ‘external’, because it is associated with optimisation of parameters external to the wind turbine design process. Tosserams et al. identify two main classes of formulations to distribute this optimisation problem over the disciplines:
nested formulations and alternating formulations. Figure 4-6 and Figure 4-7 illustrate these formulations.

The principle of the nested formulation is to divide the objective function into budgets that are assigned to the disciplines. In this case, disciplinary problems are not optimisation problems, but a search for a feasible solution within the budget. In the nested formulation, the master problem belongs to the domain of collaboration engineers and would therefore be implemented in the tool. The second role of the tool is to find feasible design solutions for the problem of the external process.

In the alternating formulation, each discipline optimises the objective function by varying only its own sub-vector variables, while maintaining the other sub vector constant. In this formulation the sub vector of the external optimisation process appears in the constraints and the objective function of the internal optimisation process. The constraints of the internal process that depend on the external sub vector can be dealt
with in the same way as done in current non-collaborative wind turbine design. For instance, the effect of wake turbulence and tower vibrations on fatigue loading of the blades can be approximated with case studies. However, the appearance of the external sub vector in the objective function leads to a double role for the tool. The tool should solve the sub problem for the external optimisation process, as well as perform the objective function computations when the internal optimisation problem is solved.

Neither of these two formulations is considered to be very suitable for the current situation. Because the master problem of the nested formulation is implemented in the tool, the tool becomes the director of the activities in the optimisation of the wind turbine. Rather than being a minimisation problem, the wind turbine optimisation becomes a repeated search for feasible wind turbines that meet the budget provided by the tool. Neither of these two characteristics of this formulation matches well with current wind turbine design practices and both would therefore require large changes in the internal process. This conflicts with the purpose of the method as formulated in Section 3.3.1 to minimise the consequences of the method for the internal design process. Furthermore, the external process also becomes a search for feasible solutions within the budget, rather a minimisation problem. This also matches poorly with current practice for several elements. This would make it complicated to build the tool on knowledge of the associated design processes in current non-collaborative development, as suggested in Section 3.4.2.

In the alternating formulation, the optimisation of the wind turbine is completed after several iterations. In each iteration, the wind turbine is optimised for new wind farm designs as defined by the fixed design variables of the external process. Compared to the current process, in which the wind turbine is optimised once, the repeated optimisation of the wind turbine demands more resources.

Instead, an alternative formulation is chosen, as shown in Figure 4-8. This formulation will be called an inner loop formulation in this thesis. The sub vector of the external process does not appear in the constraints of the internal process. As discussed for the alternating formulation, it is assumed that constraints that depend on external design variables are treated as currently done in the non-collaborative development. The boundary between the function of the tool and the function of the user is clear, since the sub vector of the external optimisation problem only appears inside the enclosed box. The only function of the tool is to optimise the system level objective function, by variation of the external design sub vector and subject to the condition that the internal design sub vector contains the values provided by the user. The minimum of the objective function under these conditions is \( k \). The user minimises \( k \) by variation of the rotor-nacelle variables in an iterative process. The communication parameters between the user and the tool are rotor-nacelle variables as input for the tool and the minimum of the objective function as output of the tool. The optimum of the problem shown in Figure 4-8 is the same as the optimum of the general formulation of Equation (4-1). However, the separation will have an, as yet unknown, effect on convergence.

The chosen inner loop formulation is not included in the two classes identified by Tosserams et al., because it does not distribute the optimisation problem over the disciplines in an way that is equal for all disciplines. Furthermore, in this formulation it
is not possible to perform the activities in the disciplines in parallel, which is usually desired in distributed optimisation.

The advantages of the inner loop formulation for the current situation are:

- The optimisation in the internal process doesn’t use the design variables of the external sub vector. The wind turbine designer therefore doesn’t need to change the turbine design process to deal with these design variables. Nevertheless, the tool could output its sub vector when needed by the user.
- The optimisation in the external process is a slave of the optimisation in the internal process. These positions of the two processes match the natural role of user and tool, in which the user is master of the proceedings.
- The optimisation in the external process effectively becomes an extensive computation of the value of the objective function for the internal optimisation. In this role, the tool can replace a previous objective function computation without the need to change the internal design process. The tool can be used in various optimisation paradigms of the user.

The external optimisation process becomes embedded inside the iterations of the internal optimisation process. This makes the progress of the internal optimisation directly dependent on the speed of the external optimisation process, since the two processes are not performed in parallel. However, since the external optimisation process is computerised, it is typically much faster than a process with human designers. Therefore, this is not considered to be a big disadvantage of the chosen formulation, although attention should be paid to the speed of the tool.

Based on the previous formulation of the use of the tool, four use cases are defined. The use cases are not intended to be complete, but they are expected to demonstrate the value of the tool. Each use case is a different algorithm for stepping through the phases in Figure 4-5.
Use case 1 - Dimensioning the turbine
The user of the tool designs several wind turbines and analyses the wind farms that the tool generates for each of these. This gives an idea of directions of change that lead to improvements and directions that are not worthwhile to pursue. This ‘trial and error’ process with different wind turbines can help finding the optimum turbine. This process can also be automated by coupling it to a wind turbine optimisation tool. In that case the tool performs the objective function evaluation for the turbine optimiser. However, this approach for turbine design is not yet common.

Use case 2 - Finding directions for improvements
The previous use case requires the effort to redesign the turbine for each trial, which makes it a time consuming activity when you want to optimise many design variables. Instead, several ‘what if’ scenarios can be tested, as a means to identify which types of modifications to the turbine could be most effective. This will be illustrated with an example: suppose the maximum thrust can be lowered by 20% without changing the purchase price of the turbine or its power performance. The tool can show how this would affect the cost of energy and other parameters of the wind farm. So, without specifying whether the lower thrust is achieved by aerodynamic redesign, changes to the pitch and speed controller or perhaps by a smart rotor, this gives an impression of what it could maximally achieve. Results of several scenarios will give an impression which properties of the wind turbine should be addressed first in an optimisation of the type of use case 1.

Use case 3 - Establishing a budget for design changes
Use case 3 is very similar to use case 2, but instead of assuming no effect on the purchase price, the purchase price is increased until the same cost of energy is achieved. The difference between the resulting purchase price and the purchase price of the reference turbine provides the maximum budget that is available for the turbine improvement.

Use case 4 - Testing market robustness
Repeating the previous use cases for different sites and farm sizes gives an impression of how sensitive the results are to these changes. The absolute values of cost of energy and other wind farm parameters will change, but more importantly, this reveals how much the optimum values of turbine parameters change for different potential applications of the turbine.

4.4 Separation of offshore wind farm dimensioning into disciplines

4.4.1 Introduction
As mentioned in Section 4.1.3, the next problem subset is to determine application-specific data and procedures and particularly how this can be further divided in smaller problem subsets. Section 3.4.2 identifies three types of application-specific information: content of a collaborative design paradigm, results of upstream design steps that are not emulated and emulation algorithms. The collaborative design paradigm that is meant here goes into more detail than the previous section and it describes the
multidisciplinary optimisation of offshore wind farms. This collaboration paradigm describes how the work is distributed over different external design groups, which corresponds to the division into problem subsets. To make this division, the external design optimisation problem needs to be known more specifically. For instance, for a more modular design solution the separation can be taken further than for a design solution with much hardware and functional integration. Therefore, the problem analysis starts with establishing the results of upstream design steps that are not emulated. After this, the collaboration paradigm is defined, leading to the division of the work and the algorithm that describes the sequence of actions and the communication in the collaborative external optimisation.

4.4.2 Fixed starting point for the design emulation

**Principles of determining the fixed starting point**

The definition of the collaborative design paradigm and the scope of the instantiation in Section 4.3 show which results of earlier design steps are fixed during the use of the tool. The fixed results are the requirements and the core concept and configuration of the elements of the wind farm. The tool is intended to be suitable to support the selection of core concepts and configuration for the rotor-nacelle assembly. Nevertheless, an initial definition of these will be given to avoid that the tool needs to be suitable for a too wide and undefined range of rotor-nacelle concepts.

Section 3.4.2 provides the guideline to establish these fixed results of upstream activities from observations of the non-collaborative developments and reverse engineering. To establish the core concepts and configurations, observations of realised wind turbines and wind farms are the most useful sources, supplemented with descriptions from literature. For many elements of the wind farm, there will be more than one option for the core concept and configuration. However, to limit the implementation effort, only one option will be chosen. It is expected that this reduction of scope for the prototype doesn’t endanger the possibility to test the utility of this type of tool, even though it may be too restrictive in real applications. This assumption was tested during the validation, which is reported in Chapter 6. The primary criterion for the selection of the core concepts and configuration is how common these are in currently realised wind farms. The selection will only be discussed when this criterion doesn’t lead to an obvious choice, or when other aspects are considered. It is acknowledge that even though the selected core concepts and configuration are most common in current wind farms, this may not be the case for future wind farms. For instance, as wind farms may become larger, farther from the coast and in deeper water, the common single HVAC transmission cable and monopile foundation may become less obvious choices.

Rather than using reverse engineering to establish the requirements, these are also determined mainly from observations of current practices from literature.

**Requirements**

In engineering design the requirements are often expressed in functions, the objective function and constraints. The functions describe what the design should do under certain conditions. The constraints define boundaries of what is acceptable and what isn’t. Each
of the design solutions that meet the constraints and perform the functions is in principle an acceptable solution. How preferable a solution is, is expressed by the objective function, which captures the performance of the design. Usually, designers strive for best performance, which means either minimising or maximising the objective function, depending on its formulation. The objective function can be subdivided in performance indicators, which express contributions to the overall performance. The performance indicators can express both negative aspects of the solution, such as costs, and positive aspects, such as the amount of produced electricity. These positive and negative aspects are combined in the objective function with weights that express their relative importance. Some optimisation approaches express constraints as penalties in the objective function, which indicates that there is a grey area in the definition of these two concepts. For clarity, in the current design problem definition events with very clear negative impact on performance are avoided by constraints, rather than with a penalty on performance. An example of such event is the total loss of a wind turbine after failure of a foundation. This section determines the functions, constraints and objective function as far as these are relevant for the scope of the instantiation.

The overall function of the system can be deduced from the specification of the system of interest in Section 4.2.2. The offshore wind farms convert energy in the wind at offshore locations and deliver this energy as electricity at a grid connection point on land. Several special functions are performed by the offshore wind farms, to maintain stability and quality of the electrical system. However, these functions are outside the scope of this prototype development. The overall function of the system is achieved through many sub-functions. These sub-functions are particularly relevant to the selection of core concepts and configurations. Since the core concepts and configurations will be determined from observations of existing solutions, these sub-functions need not be described. Furthermore, the sub-functions of offshore wind farms are often not expressed explicitly, but rather considered to be tacit knowledge of the designers.

The exact formulation of constraints depends on the chosen sub-division of functions and the selected core concepts and configuration. Otto and Wood give the example that compactness of a nail-clipper can be achieved with a configuration that enables a folding function or with a constraint on size for a non-foldable one. At this point, the constraints can therefore only be defined at a high level of abstraction. The level of detail of the formulations increases in Section 4.4.3, where all core concepts and configurations are defined and in Section 4.5, where the emulation algorithms of the external design processes are treated.

It is clear from Section 4.2.2 that the system of interest consists of components with structural, mechanical, electrical and magnetic working principles. For such components, the following constraints can be observed in engineer projects and literature:

- Structures may not fail due to instability during normal and extreme conditions
- Structures may not fail due to fatigue damage accumulated over the lifetime
- Structures may fail with limited consequential effect during accidents
- The functionality of structures may not be compromised by large motions or deflections
- Interfaces between structures and mechanisms must be geometrically compatible.
- Materials may not degrade due to overheating during normal and extreme external condition
- There may be no sparks and short circuits due to voltage breakthrough
- The existing biological, man-made and societal environment may not be disturbed at an unacceptable level, which is usually established in regulations
- Maintenance should at least be at a level that guarantees continuation of the functionality of the system

There are many more constraints, which appear when looking at more details. Furthermore, fundamental constraints or performance indicators may be translated to heuristic constraints. For instance, constraints on natural frequencies of the support structure are often introduced to simplify the design process as regards fatigue damage. Another example is the application of a constraint on magnetic flux density in transformers, to avoid saturation in the core material. Neither resonance nor saturation is by itself necessarily destructive, but it is unlikely that design solutions with such behaviour are optimal. In addition, in probabilistic approaches of engineering design the constraints and objective functions are formulated in a different way, in which constraints may be translated to penalties\textsuperscript{256, 294}. Such formulations lead to more complex optimisation problems. It is considered that the aforementioned list captures the relevant constraints and that it is sufficient for the expository instantiation.

The objective function for the collaborative design process cannot be derived unambiguously from observations of the existing non-collaborative approach. In the collaborative design process, the objective function specifies a common goal, which weighs the benefits and disadvantages for all those involved. In the non-collaborative development process, each of the design groups in Figure 4-3 has its own goal, which may be in conflict with the goal of others. A clear example is that an increase in profit of a sub-supplier may reduce the profit of the end-supplier. However, in the perspective of longer term developments of multiple offshore wind farms it is commonly acknowledged that a common goal is the reduction of costs per unit of electricity\textsuperscript{110}. Therefore, Levelised Production Costs (LPC) is chosen as objective function for the prototype of the tool. The LPC is a commonly used parameter to express attractiveness of a means to generate electricity and it is defined by Nitteberg \textit{et al.}\textsuperscript{222}:

\[
LPC = \frac{\sum_{t=0}^{T_{life}} (C_t - R_t) (1 + r)^{-t}}{\sum_{t=0}^{T_{life}} E_t (1 + r)^{-t}}
\]  

(4-2)

where:

\begin{align*}
C_t, R_t & = \text{total costs resp. revenues (outside sales of electricity) for year } t, \\
E_t & = \text{electricity production in year } t, \\
T_{life} & = \text{economic lifetime,} \\
r & = \text{real interest rate.}
\end{align*}
Other candidates for the objective function are for instance net present value, internal rate of return or a more comprehensive profit index that distinguishes profits of the contributing companies. Also, a multi criteria analysis could be implemented with additional parameters such as effectiveness of space usage or environmental impact. These alternatives have not been chosen, because the relatively simple LPC is expected to capture the essence of the objective function.

Further details of the formulation of the objective function depend on the chosen core concepts and configuration, as was the case for the constraints. The level of detail of the cost and productivity calculations increases in Section 4.4.3, where all core concepts and configurations are defined and in Section 4.5, where the emulation algorithms of the external design processes are treated.

**Core concepts and configuration of rotor-nacelle assembly**

As mentioned at the beginning of this section, the definition of core concepts and configuration of the rotor-nacelle assembly is not restrictive. The core concepts and configuration of a reference rotor-nacelle assembly are defined to determine the interfacing between this and the other elements of the wind farm. This in turn is used later to determine the type of information that needs to be communicated between the internal and external design processes. Much of the information that is communicated will also be appropriate for other core concepts and configurations of the rotor-nacelle assembly. For instance, the power curve is a characterisation that is appropriate for a very wide range of concepts. The tool is expected to be useful for any rotor-nacelle assembly concept for which reasonable interpretations can be given to the communication parameters and that perform the same functions as the reference rotor-nacelle assembly.

An overview of the chosen definitions is given in Table 4-1, which shows both the hardware and the procedures that relate to the internal design process of the rotor-nacelle assembly. Remarks are explained below the table.

**Core concepts and configuration of the wind farm elements**

The selection of the core concepts and configurations of the external designs will affect both the separation of the wind farm optimisation problem into disciplines and the emulation algorithms for the individual disciplines. For some elements no specification of the concept is given. For these elements this specification is not relevant for the further development of the tool. As will be discussed in Section 4.6.2, cost models will be used as a heuristic model of the optimisation of these elements. Although such cost models will depend on the concept of the element, it appeared that in these cases the concepts needn’t be known explicitly. The choice to define a concept or not and the equivalent choice to emulate the design discipline or to use a cost model depends on how and how much the element depends on the rotor-nacelle assembly design. The more and the more complicated the interaction between the wind farm element and the rotor-nacelle assembly, the more necessary to emulate the external design process. The decisions are made iteratively with the analysis that is given in Section 4.4.3 and using engineering intuition developed in earlier wind farm design research projects.
As concluded in Section 4.2.2, the system of interest encompasses more than one wind farm. In current practices, different wind farms rarely share hardware or activities, besides manufacturing resources and the equipment that is used during installation and maintenance. Several studies suggest the use of a shared offshore electrical infrastructure. Nevertheless, it is currently common practice to have a non-shared, direct connection between each offshore wind farm and the public grid. Because this configuration also simplifies the collaboration scheme for multiple wind farm design, as discussed in the next section, this configuration is selected.

An overview of the chosen core concepts and configurations for each individual wind farm is given in Table 4-2 and Table 4-3 for respectively hardware and procedures. Remarks are explained below the tables.

<table>
<thead>
<tr>
<th>Table 4-1 Core concepts and configuration of rotor-nacelle assembly</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concepts and configurations</td>
</tr>
<tr>
<td>----------------------------</td>
</tr>
<tr>
<td><strong>Hardware</strong></td>
</tr>
<tr>
<td>3-bladed rotor upwind of the tower</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>pitch bearings, actuators and control horizontal (main) axis</td>
</tr>
<tr>
<td>multi-stage gearbox</td>
</tr>
<tr>
<td>3-phase generator</td>
</tr>
<tr>
<td>electrical connection through back-to-</td>
</tr>
<tr>
<td>yaw bearing, actuators and control</td>
</tr>
<tr>
<td>(manufacturing and assembly not specified)</td>
</tr>
<tr>
<td>periodic service at fixed intervals (1)</td>
</tr>
<tr>
<td>corrective maintenance on demand (2)</td>
</tr>
</tbody>
</table>

Ad 1: Details of the procedures are not defined. These procedures refer only to the activities in and around the turbine, without the offshore logistics. It is assumed that service can be represented by a group of activities that all have the same interval of repetition.

Ad 2: Details of the procedures are not defined. These procedures refer only to the activities in and around the turbine, without the offshore logistics. It is assumed that corrective maintenance can be represented by categories and that all repairs in a category need similar resources and have a similar duration. For example, a category can be representative of all repairs that need only a few hours, no lifting equipment, limited consumables and no separate visit for diagnosis.

As concluded in Section 4.2.2, the system of interest encompasses more than one wind farm. In current practices, different wind farms rarely share hardware or activities, besides manufacturing resources and the equipment that is used during installation and maintenance. Several studies suggest the use of a shared offshore electrical infrastructure. Nevertheless, it is currently common practice to have a non-shared, direct connection between each offshore wind farm and the public grid. Because this configuration also simplifies the collaboration scheme for multiple wind farm design, as discussed in the next section, this configuration is selected.

An overview of the chosen core concepts and configurations for each individual wind farm is given in Table 4-2 and Table 4-3 for respectively hardware and procedures. Remarks are explained below the tables.
Table 4-2 Core concepts and configuration of wind farm hardware

<table>
<thead>
<tr>
<th>Element</th>
<th>Concepts and configurations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Layout</strong></td>
<td>Rectangular array (1)</td>
</tr>
<tr>
<td></td>
<td>Equal spacing between all columns</td>
</tr>
<tr>
<td></td>
<td>Equal spacing between all rows</td>
</tr>
<tr>
<td><strong>Support structure</strong></td>
<td>One support structure design for all positions (2)</td>
</tr>
<tr>
<td></td>
<td>Cylindrical steel tower with constant taper</td>
</tr>
<tr>
<td></td>
<td>2.4 m long tower segments with different wall thickness</td>
</tr>
<tr>
<td></td>
<td>Steel transition piece with uniform diameter and wall thickness and grouted overlapping connection with the monopile</td>
</tr>
<tr>
<td></td>
<td>Steel cylindrical monopile in sandy soil with uniform diameter and wall thickness</td>
</tr>
<tr>
<td></td>
<td>Boat landing and access platform</td>
</tr>
<tr>
<td><strong>Scour protection</strong></td>
<td>Apply when seabed would otherwise wash away</td>
</tr>
<tr>
<td></td>
<td>Made of rock (riprap)</td>
</tr>
<tr>
<td></td>
<td>One or more filter layers (as needed)</td>
</tr>
<tr>
<td><strong>Electrical collection system</strong></td>
<td>For layout, see Figure 4-9 (3)</td>
</tr>
<tr>
<td></td>
<td>Turbines in row connected to a string</td>
</tr>
<tr>
<td></td>
<td>Each string connected to the offshore platform</td>
</tr>
<tr>
<td></td>
<td>Three-phase AC</td>
</tr>
<tr>
<td></td>
<td>Single three-phase offshore cable with copper conductor and XLPE insulation</td>
</tr>
<tr>
<td></td>
<td>Cables trenched into the seabed</td>
</tr>
<tr>
<td></td>
<td>Turbine connected to string through transformer</td>
</tr>
<tr>
<td></td>
<td>Reactive power is compensated by the turbine</td>
</tr>
<tr>
<td></td>
<td>One switchgear cubicle in turbines at end of string and two in all other turbines</td>
</tr>
<tr>
<td></td>
<td>Infied cables connected to offshore transformer through bus bar with one switchgear cubicle per string plus one cubicle to disconnect all strings at once</td>
</tr>
<tr>
<td></td>
<td>No cluster control and no farm control</td>
</tr>
<tr>
<td><strong>Electrical transmission system</strong></td>
<td>Single connection from offshore platform to onshore grid connection point</td>
</tr>
<tr>
<td></td>
<td>Three-phase AC</td>
</tr>
<tr>
<td></td>
<td>Single three-phase offshore cable with copper conductor and XLPE insulation, both onshore and offshore (4)</td>
</tr>
<tr>
<td></td>
<td>Cables trenched into the seabed</td>
</tr>
<tr>
<td></td>
<td>Transformer on offshore platform and transformer at grid connection point (5)</td>
</tr>
<tr>
<td></td>
<td>Reactive power compensation onshore and offshore at both ends of the transmission cable, with passive shunt reactors (6)</td>
</tr>
<tr>
<td></td>
<td>Transmission cable connected through switchgear cubicles to transformers and reactive power compensators at both ends, thus totalling 4 cubicles</td>
</tr>
</tbody>
</table>

Ad 1: Many wind farms have slight deviations, such as a skewed array or an unequal number of turbines in each row. Often, these deviations relate to the geometry of the available area, the bathymetry and soil conditions. Since the wind turbine isn’t optimised for such specific conditions, these deviations are not considered.

Ad 2: Many wind farms have variation in support structure design for different positions within the farm, at least as regards pile length. This variation relates to the bathymetry and soil conditions. Since such specific conditions do not apply to the optimisation of the wind turbine, these variations are not considered.
Ad 3: Often, the cable strings are not along a straight line of turbines or two strings are connected in the farm with a single cable continuing to the offshore platform. Deviations from a straight line occur particularly when the layout deviates from the rectangular array. This does therefore not apply to the current layout definition. Connecting strings occurs mainly when the reduction in cable length outweighs the higher power rating that is required for the cable that connects the strings to the offshore platform. The variation in existing infield cable layouts relates to variations in the number of turbines in rows, the number of turbines in columns, the distances between the turbines and the power rating of the turbines and the position of the offshore platform. The chosen layout may not be optimal for all cases, but the simplification is expected to give reasonable results for a large variation in the aforementioned parameters.

Ad 4: When considerable distances are covered onshore, it is common to switch to three separate single phase cables with aluminium conductors for that part of the trajectory. This has not been chosen here, to simplify the implementation.

Ad 5: In wind farms that are close to the grid connection point the offshore transformer is missing. These wind farms transmit the electricity at medium voltage levels. In these cases the costs of the transformers do not outweigh the lower losses and cheaper cables that are achieved at a higher transmission voltage. Many wind farms do not use an onshore transformer, because the voltage level at the grid connection point is close to the optimum voltage level for the transmission. In these cases the use of an onshore transformer doesn’t pay off for similar reasons. The chosen configuration is therefore not optimum for all cases, but it is expected to give reasonable results for a wide range in transmission distances and grid voltages and farm rated power.

Ad 6: The type of reactive power compensation and the place of compensation in actual wind farms is not investigated. The costs of the cable and the losses in the transmission are lowest in the chosen configuration or when the compensation is done in the middle of the cable. The place of compensation in reality may depend on the costs of space on the offshore platform, the possibility to place compensation onshore close to the middle of the cable length and the desire to put compensation only at the onshore end for shorter transmission distances. The total capacity of the reactive power compensation depends on the total reactive power generated in the transmission cable. This is the dominant factor in the costs of the reactive power compensation, rather than how this compensation is placed along the cable. It is expected that less ideal configurations will give limited deviation from the results for the chosen configuration.

Figure 4-9 Layout of wind turbines and electrical collection system
Collaborative dimensioning scheme for offshore wind farms

Separation of design of multiple wind farms

In this sub section each individual wind farm is considered to be a discipline, meaning that the total design vector of the tool’s optimisation problem is split into sub-vectors with design variables of one wind farm only. The constraints and objective function are analysed for this situation, to determine the possibility of separation of the optimisation problem of the tool for this definition of disciplines.

In the previous section the choice is made that different wind farms only share manufacturing resources and the equipment that is used during installation and maintenance. If the availability of these resources is limited, this causes a constraint on the design of the wind farms. Using terminology of Tosserams et al., this type of constraint is non-separable and requires design collaboration. In this case, particularly the timing of delivery, installation and maintenance needs to be coordinated.

Site selection for multiple wind farms also requires design coordination. Legislation invariably provides exclusive rights to a single wind farm at a particular area. This implies a non-separable constraint on space usage by multiple wind farms.

---

Table 4-3 Core concepts and configuration of wind farm procedures

<table>
<thead>
<tr>
<th>Element</th>
<th>Concepts and configurations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturing</td>
<td>Not further specified</td>
</tr>
<tr>
<td>and assembly</td>
<td></td>
</tr>
<tr>
<td>Installation</td>
<td>With existing equipment</td>
</tr>
<tr>
<td></td>
<td>Not further specified</td>
</tr>
<tr>
<td>Operation</td>
<td>Not further specified</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Equipment rented on an hourly basis (as opposed to being owned)</td>
</tr>
<tr>
<td></td>
<td>One vessel type used for all access, so with a fixed speed,</td>
</tr>
<tr>
<td></td>
<td>accessibility limit and passenger capacity</td>
</tr>
<tr>
<td></td>
<td>Crew hired on a full year contract (as opposed to on an hourly</td>
</tr>
<tr>
<td></td>
<td>basis)</td>
</tr>
<tr>
<td></td>
<td>Onshore maintenance base, with monitoring facilities and</td>
</tr>
<tr>
<td></td>
<td>spare part storage</td>
</tr>
<tr>
<td></td>
<td>7 working days per week</td>
</tr>
<tr>
<td></td>
<td>Corrective and preventive maintenance during all seasons</td>
</tr>
<tr>
<td></td>
<td>Corrective maintenance has priority over preventive maintenance</td>
</tr>
<tr>
<td></td>
<td>Repair of turbines that need hoisting equipment has highest</td>
</tr>
<tr>
<td></td>
<td>priority</td>
</tr>
<tr>
<td></td>
<td>After a storm, all new failures are repaired first, before</td>
</tr>
<tr>
<td></td>
<td>continuing with repairs of failures from before the storm</td>
</tr>
<tr>
<td></td>
<td>Never more than 1 lifting vessel rented at the same time</td>
</tr>
</tbody>
</table>

Ad 1: It is common to have long-term agreements for the use of equipment, particularly for personnel access. To simplify the cost assessment, rental on an hourly basis is chosen. Effects of capacity usage ratios on hourly rates are not considered.

Ad 2: Personnel that is hired for maintenance of a particular offshore wind farm may be deployed to maintain other onshore or offshore wind turbines when they are not needed. It has not been investigated whether this is done in reality and the consequential effect on costs is not considered.

---

4.4.3 Collaborative dimensioning scheme for offshore wind farms
The requirements in Section 4.4.2 define the objective function. Substituting the contributions to the objective function of several wind farms leads to:

\[
LPC = \sum_{\text{farm } i} \left( \frac{\sum_{t=0}^{T_{\text{life } i}} \left( C_{i,t} - R_{i,t} \right) (1+r)^{-t} \left( 1+r \right)^{-t_0, i} \sum_{t=0}^{T_{\text{life } i}} E_{t,i} \left( 1+r \right)^{-t}}{\sum_{\text{farm } j} \sum_{t=0}^{T_{\text{life } j}} E_{t,j} \left( 1+r \right)^{-t}} \right) \equiv \sum_{\text{farm } i} \left( \frac{LPC_i \left( 1+r \right)^{-t_0, i} \sum_{t=0}^{T_{\text{life } i}} E_{t,i} \left( 1+r \right)^{-t}}{\sum_{\text{farm } j} \sum_{t=0}^{T_{\text{life } j}} E_{t,j} \left( 1+r \right)^{-t}} \right) \tag{4-3}
\]

in which \( i \) and \( j \) are indices to identify the costs, revenues, energy yields and lifetimes of individual wind farms and \( LPC_i \) is the levelised production cost for one farm. \( t' \) is the year in the period of duration \( T' \) that covers all wind farm lifetimes. \( t'_{0,i} \) is the year of the start of the lifetime of wind farm \( i \) in this period, implying \( t = t' - t'_{0,i} \).

Equation (4-3) shows that the objective function for multiple wind farms is a weighted average of the levelised production costs per wind farm, with the weight being the relative magnitude of the levelised total energy yield of the wind farm. Thus, farms with a high energy yield and farms that will be built in the nearest future have the highest weights in the objective function. The dependency of the weights on the energy yield in all wind farms links the performance analysis of the disciplines.

The constraints on resources and space may also lead to links in the performance that are only implicitly shown by the objective function of Equation (4-3). Limits on resources may affect the costs, following common effects of supply and demand on pricing. Second, wind farms with relatively small spatial separation mutually reduce energy yield by the reduction of the wind speed in their wakes. Thus, small separation distances have a negative effect on the objective function.

The previous analysis reveals non-separable constraints on resources and on space usage and a link between the performance analysis of the disciplines through the weighing of energy yield of different farms and the effect of the constraints on costs and energy yield. These interactions affect high level design variables of the disciplines, such as timing, total installed capacity and siting. These design variables are as close to the domain of strategic decision making as they are to engineering design, because what their optimum values are depends on a complex process with technical aspects, regulations, subsidy programs, economic climate, stakeholder attitudes etc. Mast modelled these processes and the consequential strategic choices to automatically generate scenarios for the development of offshore wind farms. This work demonstrates that this is an elaborate activity. Therefore, it is chosen not to make the optimisation of timing, total installed capacity and siting a task of the tool, but rather ask this as input from the user. Therefore, the user has to make strategic decisions about how he/she expects offshore wind energy deployment to evolve and for which type of wind farms the wind turbine is going to be designed. Possible constraints on resources...
and space should be considered when making this decision. Effectively, the wind farm sizes and site conditions need to be entered by the user and these define the market for which the wind turbine is being designed.

Even though the consideration of constraints has been made a task of the user, the evaluation of the objective function for different wind farms is still linked. The performance evaluation is reduced to the separable assessment of the levelised production costs per wind farm by making the following assumptions:

- The wind farms have sufficient separation to avoid the mutual negative influence on energy yield or this influence is insensitive to variation in the design variables
- The resources are sufficient to avoid effects on pricing or this effect is insensitive to variation in the design variables
- The optimum for the design variables of the external process is insensitive to the weighing factors

Consequentially, the tool can optimise each wind farm individually, by consideration of the levelised production costs of that wind farm as the objective function. The user can run the tool for several wind farms, according to a chosen scenario, and substitute the levelised production costs and energy yields in Equation (4-3) to obtain the overall objective function value. However, when the tool is used to optimise only one wind farm, the results reveal the performance of the wind turbine in the type of wind farm that is represented by the inputs for the farm size and the site. Therefore, separate analysis of the results for several wind farms may provide more insight than the substitution of results in Equation (4-3).

**Separation of the design process of one wind farm**

With the previous simplification for the separation of multiple wind farm designs, the tool must find optimal values of the design vector for one offshore wind farm, conditional to the inputs given by the user for the rotor-nacelle assembly, the farm size and the site conditions.

The three ingredients of this parametric optimisation problem are: the design variables of the wind farm elements, the constraints that apply to these and the levelised production costs as the objective function. The design variables and constraints have been collected for the requirements and concepts given in Section 4.4.2. Usually, the constraints are not explicitly expressed in the design variables, but rather in derived properties and behaviour. For instance, for the electrical cables a constraint is formulated that the temperature inside the cable may not exceed that temperature at which the insulation material starts to degrade. The evaluation of this constraint requires a model of the physical process of heat generation and transportation. This model needs to be expanded up to the level where it is expressed in the design variables of the wind farm and the parameters that are entered by the user. Likewise, the objective function needs to be expressed in these basic parameters. This description of the process illustrates that the dependency of the constraints and the objective function on the design variables and user input depends on the models that are selected. In the same way, the formulation of the models determines which design variables and inputs are considered. The more detailed the models, the more design variables are needed to
express the details of the design solution. To simplify the implementation of the tool and to achieve short optimisation times, simple models are selected for a relatively small set of design variables. This is suitable for preliminary design optimisation, as targeted by the scope of the tool as chosen in Section 4.3.2.

In first instance, the design variables and input parameters as well as the dependency of the constraints and the objective function on these parameters have been identified based on qualitative model descriptions. For instance, it has been established that the temperature in the cable depends on the current through the cable, the geometry of the cable, the material properties of the cable layers, the surrounding soil temperature etc., without specifying a mathematical model. These model descriptions are based on earlier design experience and literature. The mathematical models and constraints formulations that are eventually used are discussed and presented with references in Section 4.5, where the algorithms per separated wind farm design discipline are reported. Therefore, an overview of the results of this process is given in Figure 4-10, without references to support the intermediate steps.

Not all details of the design variables and constraints are shown in this figure and several dependencies of the objective function and constraints have been neglected. For

<table>
<thead>
<tr>
<th>Levelised production costs</th>
<th>x</th>
<th>x</th>
<th>x</th>
<th>x</th>
<th>x</th>
<th>x</th>
<th>x</th>
<th>x</th>
<th>x</th>
<th>x</th>
<th>x</th>
<th>x</th>
<th>x</th>
<th>x</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clearance platform and blade tip</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Limit states under loads</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Limit states in waves and current</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Filter layer may not wash away</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Soil may not wash away</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Excluded areas</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Temperature limit insulation</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>No voltage breakthrough</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<td>x</td>
<td>x</td>
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<tr>
<td>Temperature limit insulation</td>
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<td>x</td>
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<td>x</td>
</tr>
<tr>
<td>No voltage breakthrough</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<td>x</td>
<td>x</td>
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<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>No voltage breakthrough</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>All failures repaired eventually</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

*Figure 4-10 Overview of design variables and their appearance in the objective function and constraints*
instance, the effect of spacing between rows on the loads in the support structure has been neglected. This effect is caused by the level of turbulence in the wake, which is a function of the distance behind the turbine. Several of these simplifications in the models have been made to make it possible to organise the dependencies in groups. The first group, on the left-hand side, is formed by the input parameters. These appear in many constraints. However, for the optimisation problem of the tool, these parameters have a fixed value and need not be optimised. The other groups are distributed along the diagonal of the matrix, without overlap. This means that the constraints are separable over the sub design vectors that correspond to each group of constraints. The sub design vectors define the disciplines of the wind farm optimisation process. With this definition of disciplines, the optimisation problem can be divided in smaller optimisation problems per discipline. The disciplines only have to deal with constraints on their own design variables. For this type of distributed optimisation local convergence can be proven, even though the objective function depends on design variables of all disciplines. Furthermore, in case of separable constraints the distributed optimisation can be implemented without the need to relax consistency between the sub-optimisations or the constraints. This simplifies the algorithms and increases the speed of convergence.

The disciplines that can be identified in Figure 4-10 are: support structure, layout, electrical system and maintenance. A fifth discipline is formed for other components and procedures for which no details of the design variables and constraints are formulated at this point. Section 4.6.2 discusses that the design variables of this fifth discipline will not be optimised explicitly by the tool. Therefore, this discipline is not implemented with an engineering model. However, its consequence for the objective function will be represented by cost models.

**Objective function formulation and separation of its evaluation**

Figure 4-10 shows that the objective function is a function of the design variables of all disciplines. The objective function needs to be evaluated in each iteration step, but during the optimisation of one discipline only the variables of that discipline have changing values. Therefore, it would be convenient to decompose the objective function in smaller contributing performance indicators. Some of these performance indicators may be a function of design variables of only a few disciplines and would therefore only need to be updated during the optimisations of these disciplines. During the optimisations of the other disciplines, their contribution to the objective function remains constant and doesn’t need re-evaluation. This separation of the objective function isn’t necessary for convergence of the optimisation, as it is for the constraints. However, it saves computational time to update only relevant contributions.

The cost contributions of the LPC can be separated in parts that depend on only one or two disciplines. There are very few mutual dependencies between cost contributions in reality and these have been neglected. For instance, rental costs of lifting equipment could be lowered when the same equipment is contracted for installation and for maintenance. The separation into cost contributions has initially been done based on the list of system elements of Section 4.2.2, the configuration definition of Section 4.4.2 and various cost models from literature. Eventually, the list is detailed using the detailed models that are derived in Section 4.6, where also specific references are given.
derived separation of the costs, corresponding to the numerator of Equation (4-2), is given in Appendix B. The appendix also shows when each of the contributions needs to be updated.

The energy yield, which appears in the numerator of the objective function, is the integral of the power at the grid connection point over the lifetime of the wind farm. The power at the grid connection point consists of the summation of the power coming from each of the turbines, minus the losses in the electrical system. Representing the latter effect by the electrical efficiency, the energy yield becomes:

\[
E = \int_{t=0}^{T} \left( \eta_{\text{electrical}}(t) \sum_{i=1}^{N_t} (\eta_{\text{availability},i}(t) \cdot \eta_{\text{array},i}(t) \cdot P(V)) \right) dt
\]

in which:

- \( N_t \) = number of turbines in farm,
- \( \eta \) = efficiency,
- \( P(V) \) = power as a function of undisturbed wind speed,

and:

\[
\eta_{\text{array},i}(t) = \frac{P_i(t)}{P(V)}
\]

with:

- \( P_i(t) \) = power as a function of time.

The array efficiency of the turbine expresses how effectively it is deployed at a specific instance, by comparison of the actual power of that wind turbine with a wind turbine that would operate in the ambient wind speed. This efficiency is reduced by the wind speed deficiency caused by the wakes. A similar term could be added to express the effect of power control of the wind farm. However, farm control is not applied in the chosen farm configuration. Equation (4-5) removes some of the time dependency of the power of individual turbines and replaces it with a wind speed dependency. The wind speed is still a function of time, but this is not shown explicitly in the equation. To further remove the explicit time dependency, the efficiencies \( \eta \) are rewritten with a time independent efficiency, \( \eta \), and a fluctuation, \( \varepsilon \):

\[
\eta_{j,i}(t) = \eta_j + \varepsilon_{j,i}(t)
\]

The index \( j \) replaces the textual indices of Equation (4-4). The index \( i \) is actually not relevant to the electrical efficiency. The time independent efficiency will further just be called efficiency. This efficiency is always between 0 and 1. The instantaneous efficiency is nominally also between 0 and 1, but can exceed this range instantaneously,
due to dynamic behaviour of the system. Therefore the fluctuation is also nominally between 0 and 1. Substitution of this expression in Equation (4-4) leads to:

\[
E = N_0 \int_{t=0}^{T} \prod_{j} \eta_j \cdot P(V) \cdot dt + \int_{t=0}^{T} \sum_{i \neq j} \sum_{k} \varepsilon_j(t) \prod_{k \neq j} \eta_k \cdot P(V) \cdot dt + \int_{t=0}^{T} \sum_{i} \sum_{j} \sum_{k} \varepsilon_j(t) \cdot \varepsilon_i(t) \prod_{k \neq j \neq i} \eta_k \cdot P(V) \cdot dt + O(\varepsilon^3) \tag{4-7}
\]

The first term on the right-hand side doesn’t contain any explicit time dependency and can be translated to a summation of the energy yield per wind bin, according to:

\[
N_0 \int_{t=0}^{T} \prod_{j} \eta_j \cdot P(V) \cdot dt \approx N_0 \prod_{j} \eta_j \cdot \sum_{\varphi} \left( \sum_{V_\varphi} P(V) f_\varphi(V) \Delta V_\varphi \right) \cdot f(\varphi) \Delta \varphi \tag{4-8}
\]

with:

- \(f_\varphi(V)\) = probability density function of wind speed \(V\) in direction \(\varphi\),
- \(f(\varphi)\) = probability density function of wind direction \(\varphi\),
- \(\Delta V\) = width of wind speed bin,
- \(\Delta \varphi\) = width of wind direction bin.

The efficiencies can be defined such that each of the contributions to the summation over \(j\) in the second right-hand term of Equation (4-7) equals zero according to:

\[
\int_{t=0}^{T} \sum_{N_{\text{turbines}}} \varepsilon_j(t) \prod_{k \neq j} \eta_k \cdot P(V) \cdot dt \equiv 0 \quad \Leftrightarrow \quad \eta_j \equiv \frac{\int_{t=0}^{T} \sum_{N_{\text{turbines}}} \varepsilon_j(t) \cdot P(V) \cdot dt}{N_{\text{turbines}} \int_{t=0}^{T} P(V) \cdot dt} \tag{4-9}
\]

which is obtained by re-substitution of the definitions of the time independent efficiencies. In words, this equation means that the efficiency is expressed in terms of the lifetime energy yield relative to the lifetime yield that would be achieved without the associated loss factor.

Equation (4-9) appears to separate the determination of the various efficiency factors. However, the instantaneous efficiency is still a function of the other efficiencies. For instance, the efficiency of the transmission cable is higher at low currents and therefore higher when there are more wake losses. This correlation between the efficiencies will be neglected. Furthermore, the efficiencies will be determined as a function of wind speed and wind direction, such that Equation (4-9) can be solved by a summation over bins for wind speed and direction, in the same way as Equation (4-8). The correlation between the various instantaneous efficiencies also affects the third and higher order terms in Equation (4-7). If the fluctuations are uncorrelated, these terms are zero, but as discussed above there is some correlation. However, since all efficiencies are close to 1,
the correlations in their fluctuations are very small. A more accurate model could be achieved by defining an average efficiency per wind speed and wind direction bin, to avoid most of the correlation. To keep computation times down, this has not been done in this project.

The previous analysis shows that correlation between the losses has two effects on accuracy of the model for energy yield. The first effect comes directly from neglect of the correlation in the physical models of the instantaneous losses. The second effect is an arithmetic error that results from the decomposition of energy yield in efficiencies, using the definitions of Equation (4-9).

The final model for the energy yield estimation is:

\[
E = N_t \cdot \eta_{\text{electrical}} \eta_{\text{array}} \eta_{\text{availability}} \sum_{\varphi} \left( \sum_{V} P(V) f_{\varphi}(V) \Delta V \right) \cdot f(\varphi) \Delta \varphi
\]  

(4-10)

in which the efficiencies are determined according to:

\[
\eta_j = 1 - \frac{\sum_{\varphi} \left( \sum_{V} P_{\text{loss},j,\varphi}(V) f_{\varphi}(V) \Delta V \right) \cdot f(\varphi) \Delta \varphi}{N_t \cdot \sum_{\varphi} \left( \sum_{V} P(V) f_{\varphi}(V) \Delta V \right) \cdot f(\varphi) \Delta \varphi}
\]

(4-11)

with:

\[P_{\text{loss},j,\varphi}(V) = \text{loss of power due to effect } j \text{ for wind coming from direction } \varphi.\]

The double summation provides an estimate of the energy yield of a solitary wind turbine. Appendix B lists when each of the efficiencies in Equation (4-10) needs to be updated. The electrical efficiency is determined from several loss factors, which are only updated when relevant parts of the electrical system have changed. It is expected that the update of the array efficiency is particularly time consuming and therefore it is convenient that it only needs to be updated during the layout optimisation. In effect, array efficiency also depends on the hub height, which changes during the support structure optimisation. When hub height changes, the wind conditions in which the turbines operate change, due to the wind shear. However, this effect has been neglected to save the need to update array losses during the optimisation of tower lengths.

**Sequencing of design processes**

Section 4.3.3 shows the nested and the alternating formulation of distributed optimisation. According to Tosserams et al.\textsuperscript{274}, an alternating scheme has the advantage that its associated disciplinary optimisation problems are typically smooth and well-posed. In an alternating formulation each discipline optimises its design variables, whereas in a nested formulation each discipline searches a design solution that meets the specified budgets. The first approach matches better with the design practices seen in reality, because this doesn’t require the coordinating activity of optimising the
budgets to achieve an optimum solution. This match with reality makes it easier to model the design disciplines, because it enables the use of knowledge from experience in real wind farm design projects. Therefore, an alternating formulation is chosen.

The alternating formulation can be implemented in a sequential scheme, a parallel scheme, or a combination of the two. A parallel scheme facilitates parallel computing, whereas a sequential scheme benefits from immediate use of the new optimal design after a discipline has finished. Since the prototype of the tool is intended to be used by various testers, it is desirable that it can be run on a single desktop or laptop computer, without capabilities for parallel computing. Therefore, a sequential Gauss-Seidel alternating scheme is chosen. Before entering the sequential process, initial values have to be assigned to all of the design variables. The sequence of processes is illustrated in Figure 4-11. The loops through the disciplines continue until the reduction in the objective functions at the end of two consecutive iterations drops below a selected value or when a pre-set number of iterations has been achieved. In the prototype, these stopping criteria are set at 0.01% improvement and 10 iterations, respectively.

4.5 Disciplinary design processes

4.5.1 Generic problem analysis

After separation of the constraints, the remaining design problem of each discipline is to find the minimum of the LPC by variation of its own design variables, subject to constraints that also depend only on its own design variables. On an abstract level, these design problems of each discipline have much in common. Therefore, this section discusses the common elements of solving these problems in the tool. The specific completion per discipline is treated in the sections that follow this generic analysis.

The optimisation that remains for discipline \( j \) is specified by the following equation:

\[
\min_{\mathbf{x}_j} f(y, \mathbf{x}_j, ..., \mathbf{x}_M) \\
\text{s.t.} \quad g_j(\mathbf{x}_j) \leq 0 \\
\quad h_j(\mathbf{x}_j) = 0
\]  

(4-12)

Figure 4-11 Sequence of disciplinary optimisations
This type of problem is illustrated in Figure 4-12 for a discipline with two design variables. Since the design variables are independent, they can take all values along the horizontal and vertical axis, respectively. The space that is defined by the two axes is called the design space. The elliptic curves are lines with equal levelised production costs, as a function of the two design variables. The position and shape of these lines change when the design variables of the other disciplines get different values, but during optimisation inside one discipline they remain fixed. The lines with the dashed side represent the constraints. Points in the design space that are on the dashed side of a line are not acceptable. Points that are on the acceptable side of these lines are called feasible points, or feasible designs. For equality constraints, both sides of the line would be dashed and only points on the line itself are feasible. This is not shown in the figure. The feasible point with the lowest LPC is the solution of the optimisation problem. The lines with equal LPC help to visually determine this point in the figure. This solution can be on a constraint line, in which case it is called a bound acceptable point. If it is not on a constraint line, it is called a free point.

To design the algorithms that solve the optimisation problems for the disciplines in the tool, three properties have been considered to be of most importance. First, the tool needs to be quick. The software that is developed is a prototype with the purpose to be tested by potential users. The tool needs to be quick to avoid wasting time of the testers and to keep them comfortable with spending time in the test program. This may come at the cost of reduced accuracy, since the results of the tool are not intended to be used beyond the test. Second, it is very important that the optimisation always finds a solution. This is a general requirement, that doesn’t only apply to this prototype. Since the users are considered to be inexpert in the domain of the implemented disciplines, they cannot be expected to intervene during runs of the tool to help it find a solution. Many optimisation algorithms need to start with an initial guess that is a feasible design, so it must also be ensured that such a starting point is used in these algorithms. Third, the LPC that is determined by the tool should not have unnecessary irregular response.

Figure 4-12 Graphic representation of disciplinary design optimisation for two design variables; Meaning of lines and points is given in the text
to input parameters. The LPC is used in the optimisation of the rotor-nacelle assembly and if it has irregular behaviour, this optimisation process becomes more difficult. With ‘unnecessary’ is meant for instance that the irregularities are at a scale that is below the expected accuracy of the outcome. Such irregularities could be smoothed out without loss of accuracy.

The following principles are applied to achieve these properties. For each principle an example is given below the list.

1. Achieve short computational times:
   a. Use heuristic design knowledge to explicitly express the estimated optimal value of a design variable in terms of other design variables and input parameters
   b. Use heuristic knowledge or logical analysis of the optimisation problem to determine whether the optimum is a free point or a bound acceptable point
   c. Use an efficient order for solving the design variables: First solve those that are only a function of input parameters, then solve those that are a function of input parameters and previously solved design variables etc.
   d. Use simple models that are fast to solve and that may help to apply the other principles. However, the selected models should be detailed enough to include the sensitivity to the most relevant design variables and inputs

2. Achieve stable performance of the optimisation:
   a. Separate the problem in problems with less design variables, for which the character of the response can more easily be analysed. The smaller problems can be combined as shown in Figure 4-8 or be performed in parallel if they have separable constraints
   b. Determine a solution algorithm that matches the character of the response of the objective function and constraints. This may include establishing appropriate boundaries or starting values for the design variables
   c. For the smaller design problems achieved with principle 2.a, assess the constraints to find an analytical expression for a feasible initial guess

3. Achieve a smooth response of LPC to changes in input parameters:
   a. Avoid the use of standardised components as design solutions, because this only allows discrete points in the design space
   b. Avoid models that use random values, such as Monte Carlo simulations

Ad 1.a: The diameter of the tower top is set equal to the diameter of the yaw bearing. This geometric compatibility, without a structure to overcome a transition, is observed in practice.

Ad 1.b: An example of heuristic knowledge is that offshore turbines are claimed to have their optimum hub height as low as possible. The costs of increasing hub height may not be outweighed by extra energy yield if the wind speed doesn’t increase much with height. An example of a logical analysis is that the optimisation of thickness of the monopile corresponds to finding a bound acceptable point. This is further explained in the design rules of the disciplinary optimisation of the support structure.

Ad 1.c: As can be seen from the example of 1.a, the diameter of the tower top can be determined immediately from the input parameters. To determine an efficient
order, the dependency of constraints, parts of the objective function and heuristic rules of 1.a and 1.b are written in a matrix, similar to Figure 4-10. By moving rows and columns, a triangularly filled matrix can be formed that shows in which order the design variables can be solved efficiently, similar to the way in which a normal set of linear equations can be solved.

Ad 1.d: The gravity load of the tower on the transition piece and monopile is assessed using a simple model to estimate preliminary values of the tower wall thicknesses. By doing this, the transition piece and monopile can be designed without iterating the tower wall thicknesses in the same loop. The final tower wall thickness design is done separately in a later step.

Ad 2.a: The optimisation of cable dimensions and voltage level transformations in the electrical system can be separated. The optimisation of the infield cable and transmission cable can be performed mutually independent, while these cable designs can be an inner loop in the design of voltage level transformations. The matrix that is developed for principle 1.c also helps in this separation of the problem.

Ad 2.b: If the hub height is optimised, rather than being fixed at the lowest possible height as in the example of 1.a, than the minimum allowed hub height sets the minimum of the range for the tower length optimisation. When tower length increases, both energy yield and tower costs increase. With the chosen models, both increase monotonically. Initially, the effect of increased energy yield on the LPC may be larger than that of the tower costs. However, at higher altitudes the increase in energy yield levels off, while the tower costs keep increasing. Therefore, LPC is a smooth function of tower length that may or may not decrease initially, but will eventually increase. This type of response is very suitable for a simple gradient optimisation algorithm. There is no clear upper bound for this optimisation, when no constraints are formulated on for instance transportability and manufacturability. Based on observations in practice, a maximum tower length above the platform of 200 m is a reasonable upper boundary.

Ad 2.c: In the example of 2.b, the tower length that corresponds with the minimum hub height is a feasible design. This tower length can easily be determined.

Ad 3.a: Instead of using standard electrical cables the tool makes an engineering design without being restricted to standard cables. For transformers and installation equipment, curve fits to standard solutions have been used to interpolate properties of intermediate solutions.

Ad 3.b: A common approach for the assessment of maintenance performance is to apply Monte Carlo simulation. A new model is developed that expresses maintenance performance in analytical functions. This new model is further explained in Section 4.7.

The principles described above clearly require formulations of constraints, parts of the objective function and heuristic rules, before they can be applied. On the other hand, pre-knowledge of the principles may sometimes stimulate simplifications in these formulations, such that the principles can be applied more effectively. This leads to a process with some toing and froing between models, constraints and objective function formulations and the simplifications that enable the faster and more stable algorithms. The final design algorithms are presented in a top-down order. This means that first the sequence of the solution of design variables is shown. After this follows the
determination of an initial guess. This initial guess is needed before the optimisation can start, as shown in Figure 4-11, because it is used in the evaluation of the objective function in the first disciplinary optimisation. The initial guess is followed by a description of generally applied simplifications and the design rules that are used to solve each of the design variables. These design rules may be the mathematical formulations of heuristic knowledge, the evaluation of a bound point on a constraint or the optimisation algorithms with their search boundaries. These three possibilities are denoted by ‘Knowledge Based Engineering (KBE) rule’, ‘On constraint’ and ‘Optimisation’, respectively, in the overviews of the algorithms.

The descriptions of the design algorithms and models are intended to be complete, such that the reader can judge their value. However, describing all considerations that led to their selection would make the text very lengthy. Therefore, emphasis is put on the final result. The design rules and a brief explanation of their rationale are separated by a horizontal line, like this:

---

Readers that are not interested in details of the design algorithms can continue with the next chapter, without missing essential information to follow the storyline of the next chapters.

### 4.5.2 Support structure

#### Overview of the algorithm

Table 4-4 shows the algorithm of the support structure design. The tower top diameter and the transition piece length are determined from input parameters. Since all other design variables are linked to the tower length, through the constraints or the KBE rules, they are assigned values inside the tower length optimisation loop. The design variables in the loop of the monopile diameter appear in its constraints through the load calculations. The tower wall thicknesses and transition piece wall thickness are also needed in the gravity load calculation. However, since these have minor influence on the monopile diameter a preliminary estimate of these thicknesses is used in this loop and their designed values are determined later. The other design variables can be processed sequentially.

#### Initial guess

Only tower length is optimised in the design algorithm and therefore it needs to be assigned an initial value that leads to a feasible solution. Tower length appears in two constraints that require the tip of the blade to retain a clearance above maximum sea level and above the platform, respectively. These constraints can be evaluated from input parameters, as will be explained when the design rules are discussed in the next sub section. The initial tower length is set at the minimum that meets these constraints. The other design variables get their initial guess following the design algorithm, for which no evaluation with design variables of other disciplines is needed.

#### General simplifications

Dominant constraints on the support structure design solutions are the limit states, which are defined in the standards. The limit states for fatigue, accidental...
loading and serviceability are neglected. Furthermore, the loads in the ultimate limit state are determined for a limited set of load cases using an analysis of the static response only. The load cases that are evaluated are:

- operation, rated wind speed, maximum wave in one-year extreme sea state
- parked, reduced gust in 50-year average wind speed, maximum wave in 50-year extreme sea state
- parked, maximum gust in 50-year average wind speed, reduced wave in 50-year extreme sea state

Safety factors and definitions of external conditions correspond with standard IEC 61400-3. An additional safety factor of 1.5 is applied to the loads to compensate for the neglect of fatigue. This safety factor is not applied in the assessment of the monopile penetration depth, which is not driven by fatigue.

**Discussion of selected design rules**

**Tower top diameter**
As stated in the example ad 1.a of Section 4.5.1, the tower top diameter is set equal to the yaw bearing diameter.

**Transition piece length**
Platform height is set at the minimum allowed in IEC 61400-3. This is at the maximum water elevation plus a margin for run-up of waves against the structure. The latter is prescribed to be 0.2 times the maximum wave height, with a minimum of 1 m. The bottom of the transition piece is chosen to be at 6 m above the seabed or below the lowest water elevation, whichever of the two is lowest.
The rationale to take the lowest acceptable transitions from monopile to transition piece and from transition piece to tower is that at both transitions it is expected to be more costly to extend the lower structure than the upper structure. The choice of platform height is confirmed by the structures at Offshore Windpark Egmond aan Zee (OWEZ), which have a run-up margin of 1.5 m\(^2\). At these structures the base of the transition piece is at approximately 8 m above the seabed, while it is only a few meters at Horns Rev I\(^9\). There is too much variation in transition piece length to assume a fixed length, considering for instance lengths of 17, 23 and 27 m at Horns Rev II\(^4\), Greater Gabbard\(^199\) and OWEZ\(^223\), respectively.

**Tower length**

The tower length is being optimised. The optimisation of tower length has a lower bound, which is determined by the two constraints that require the tip of the blade to retain a clearance above maximum sea level and above the platform, respectively. The first constraint depends on local regulations and is set at 20 m clearance with highest astronomical tide. The second constraint is formulated by IEC for save working conditions\(^153\) and is chosen to be 4 m clearance above the platform. The upper bound for tower length is set at 200 m. As discussed in the example ad 2.b in Section 4.5.1, no constraint is formulated that would lead to an upper bound, but based on realisations in practice it is assumed that the optimum will be found at a length shorter than 200 m.

Of the available optimisation algorithms in Python libraries, an implementation of the sequential least squares programming algorithm is chosen\(^175, 269\). As discussed in the same example, LPC is a smooth function of tower length and it has a single minimum, which is potentially at the lower bound.

Given the fixed height of the platform, the tower length determines the hub height. Variation of hub height thus influences both numerator and denominator of the LPC, through support structure costs and energy yield, respectively. The consequence of these two opposing effects cannot be known a priory, although it is generally considered that increasing hub height over the acceptable minimum doesn’t pay off at offshore sites. Nevertheless, an optimisation is chosen, because this general rule may not apply to all sites and to smaller rotor diameters.

**Monopile diameter**

The monopile diameter is determined by finding the diameter at which the maximum stress in the pile equals the yield stress for each of the three load cases. It is assumed that maximum stresses occur at the mudline, although it is known that in a uniform monopile they would occur at a lower level. The largest of the three resulting diameters is chosen. The search for the diameter where stress and yield stress equate is formulated as a root finding problem, by subtracting the stress from the yield stress. Of the available root finding algorithms in Python libraries, an implementation of Brent’s algorithm\(^268\) is chosen. The interval for the tried diameters is fixed to 0.01 – 1000 m. The design variables that appear inside the iteration, as shown in the overview of the algorithm, are made a function of the monopile diameter. In addition, tower wall thicknesses are approximated by 1/200 times the local tower diameter and the transition piece wall thickness are approximated by 1/50 times its diameter.
The difference between yield stress and stress leads to negative values for underestimations, while it yields positive values for overestimations of the diameter and it is a monotonically increasing function. Based on realisations in practice, the chosen range is expected to contain the root of the problem and it is therefore a sign changing interval. For such interval, the chosen algorithm is claimed to guarantee convergence (The Scipy Community referring to Brent).

To determine the stress in the pile, the loads on the support structure and the moment of resistance of the circular cross-section need to be known. Therefore, all dimensions of the support structure need to be established. The outer dimensions are needed to determine the aerodynamic and hydrodynamic loads, the wall thicknesses are needed to determine the gravity loads and the wall thickness of the monopile is needed to determine the moment of resistance. As will be argued in the design rules below, the outer dimensions and the wall thickness of the monopile can be made a function of the monopile diameter. The wall thicknesses of the tower and the transition piece can’t be determined that easily. However, since they are only used in the less important determination of the gravity loads, a preliminary estimate is used.

The following three considerations support that this monopile diameter approximates the optimum:

- With the chosen relations between support structure geometry and monopile diameter, the mass increases monotonically with the diameter. Since costs are assumed to increase monotonically with mass and appear in the numerator of the LPC, the mass should be minimised. Therefore, the optimum for monopile diameter is a bound acceptable point on the constraint for the ultimate limit state.
- As will be shown later, the constraint on local buckling during pile driving leads to a minimum requirement for the wall thickness. The moment of resistance of the cross-sectional area of the monopile increases more rapidly with diameter than with wall thickness, while the effect of both parameters on mass is approximately linear. Therefore, large diameters are more preferable than large wall thicknesses and it is not necessary to search for solutions with a wall thickness larger than the required minimum. Because the risk of buckling during pile driving sets a much more demanding constraint than buckling during lifetime loading, the ultimate limit state in the monopile is only checked for yield stress and not for buckling stress.
- In a later phase in the support structure optimisation the estimates of tower and transition piece wall thicknesses are replaced using more comprehensive design rules. This will change the dependency of these wall thicknesses on the monopile diameter from the preliminary estimates. Therefore, the real optimum monopile diameter may differ from the one found here. However, this effect has been neglected since variation of the monopile diameter is expected to have a much stronger effect on the costs of the monopile itself than on the costs of the transition piece and tower.

**Monopile wall thickness**

The monopile wall thickness, \( t_{pile} \), is made a function of its diameter, \( D_{pile} \), according to:

\[
t_{pile} = 0.0635 + 0.01 \cdot D_{pile}
\] (4-13)
According to the American Petroleum Institute (API), this is a minimum wall thickness to avoid buckling during pile driving\(^\text{10}\). Since the wall thickness only contributes to costs, in the numerator of the LPC, it is clear that the optimum design is obtained with the smallest acceptable wall thickness.

**Transition piece diameter**

The outer diameter of the transition piece is taken to be 300 mm larger than outer diameter of monopile.

This choice of diameter leaves an annulus of about 100 mm, considering a wall thickness of the transition piece of about 50 mm. This choice is based on the observations that are shown in Table 4-5.

**Tower base diameter**

The tower base diameter is set equal to the transition piece diameter.

It is observed in practice that these diameters are nearly equal, since this provides an effective transfer of loads from the tower to the transition piece. This rationale is similar to that for equating tower top diameter to yaw bearing diameter.

**Transition piece overlap with monopile**

The overlap length of the transition piece, \(l\text{\_overlap}\), has been related to the outer diameter of the monopile through:

\[
l\text{\_overlap} = 1.44 \cdot D\text{\_pile}
\]

(4-14)

According to Dedic\(^\text{78}\), the overlap length is typically between 1.3 and 1.6 times the monopile diameter. A linear regression between the overlap length and monopile diameter for Horns Rev\(^\text{84,90}\), Barrow\(^\text{84}\), Samso\(^\text{83,84}\) and OWEZ\(^\text{223}\) resulted in:

\[
l\text{\_overlap} = 1.07 \cdot D\text{\_pile} + 1.65
\]

(4-15)

<table>
<thead>
<tr>
<th>Farm</th>
<th>Monopile diameter [m]</th>
<th>Transition piece diameter [m]</th>
<th>Annulus [mm]</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samsø</td>
<td>4.5</td>
<td>4.82</td>
<td>115</td>
<td>83</td>
</tr>
<tr>
<td>Samsø</td>
<td></td>
<td></td>
<td>110</td>
<td>84</td>
</tr>
<tr>
<td>Rhyl flats</td>
<td>4.7</td>
<td>5.0</td>
<td></td>
<td>213</td>
</tr>
<tr>
<td>Lynn and Inner Dowising</td>
<td>4.74</td>
<td>5.0</td>
<td></td>
<td>212</td>
</tr>
<tr>
<td>Horns Rev I</td>
<td>3.9</td>
<td>4.2</td>
<td>80</td>
<td>84</td>
</tr>
<tr>
<td>Horns Rev II</td>
<td></td>
<td></td>
<td>50-125</td>
<td>4</td>
</tr>
<tr>
<td>-</td>
<td></td>
<td></td>
<td>90</td>
<td>78</td>
</tr>
<tr>
<td>(Baltic sea – not realised)</td>
<td></td>
<td></td>
<td></td>
<td>246</td>
</tr>
</tbody>
</table>
but the gradient is very uncertain due to scatter in the data. The equation that is used is a linear regression through the same data, which is force through the origin.

**Monopile penetration depth**
The monopile penetration depth is taken to be 1.1 times the largest clamping depth that is found with Blum’s model for laterally loaded piles for the three load cases. The loads are divided by a safety factor on the bearing capacity of the pile of 0.8, in line with the API\textsuperscript{10}.

From foundation design and analysis for many monopiles, it has become clear that the lateral loading of the pile is much more important than the vertical, axial loading. The clamping depth determined with Blum’s model indicates the extent of soil that is active in bearing the loads. Since Blum’s model assumes that clamping takes place at a singular point at the pile end, the pile penetration depth is taken to be 10% more than the clamping depth, to compensate for this simplification. Since the penetration depth only appears in the costs in the numerator of the LPC, it is clear that the optimum design is a bound acceptable point obtained with the smallest penetration depth that resists all loading.

**Monopile length**
The monopile length can be determined from the height of the transition piece base, the overlap length of the transition piece and its penetration depth. The height of the transition piece base is discussed in the sub section on the transition piece length.

**Tower wall thicknesses**
The tower wall thickness per segment of the tower is determined by finding the thickness at which the maximum combined stress in the pile equals the critical stress for each of the three load cases. The combined stress and critical stress include the effects of axial loading, bending and buckling, following the guidelines of Det Norske Veritas\textsuperscript{87}. The evaluation is performed at the base of each segment. The largest of the three resulting wall thicknesses per segment is chosen. The search for the wall thickness is formulated as a root finding problem, by subtracting the combined stress from the critical stress. Brent’s algorithm\textsuperscript{268} is chosen again to solve this problem. The interval for the tried wall thicknesses starts at a thickness that is 10% larger than the thickness at which Euler buckling would occur and ends at the local tower radius. This procedure to update the initial guess of the tower wall thickness from the design rule for monopile diameter goes from the tower top down, such that the gravity loads are determined with the final values.

The difference between critical stress and combined stress leads to negative values for underestimations of the wall thickness, while it yields positive values for overestimations and it is a monotonically increasing function. The wall thickness at which Euler buckling would occur leads to a singularity in the constraint and therefore the lower bound is set at a 10% larger thickness. The reason for the upper bound is clear. Based on realisations in practice, the chosen range is expected to contain the root of the problem and it is therefore a sign changing interval.
Since the wall thicknesses only contribute to costs, in the numerator of the LPC, it is clear that the optimum design is obtained with the smallest acceptable wall thicknesses.

**Transition piece wall thickness**

The wall thickness of the transition piece is determined in the same way as the tower wall thicknesses. The maximum stresses are assumed to be at the top of the monopile, where the overlap between monopile and transition piece starts. For parts of the structure above mean sea level the aerodynamic loads are determined, while hydrodynamic loads are determined for the transition piece below mean sea level. A stress concentration factor of 1.2 is applied to the bending moment for expected stress concentration in the overlap and to represent that maximum stresses will actually occur at a slightly lower level.

**Scour protection armour layer grading**

The grading of the armour layer is determined by finding the $d_{50}$ at which the characteristic shear stress on the rocks equals the critical stress. The critical shear stress is determined from the critical Shields parameter. The characteristic shear stress is determined for a wave with the 50-year extreme significant wave height and peak period, combined with the depth averaged 50-year extreme current. Wave motion is determined at the seabed and includes the maximum increase due to presence of the pile.

This root finding problem is also solved with the implementation of Brent’s algorithm. The interval for the tried rock grading starts at a $d_{50}$ of $1 \cdot 10^{-9}$ m and ends at the water depth. The lower bound is several orders smaller than typical values for sandy soil and the upper bound is the largest rock size that would still be submerged. For normal situations it is expected that this is a sign changing interval. When the solution is smaller than $d_{50}$ of the soil, no scour protection is needed and scour protection costs will be set at zero.

The use of the Shields threshold approach to determine the minimum rock grading that is stable under current and wave loading is described in many sources. Some sources describe the equality criterion for the critical and characteristic shear friction that is chosen here, while others describe measurements where rocks become unstable when shear stress exceeds a threshold of approximately 0.4-0.5 times the critical shear stress. However, these reports appear to estimate the characteristic shear stress without consideration of the water particle accelerations around the pile. A realistic velocity increase of 1.5 times could explain the difference, because this would lead to maximum shear stresses that are 1/0.44 times larger than those calculated for undisturbed conditions. The range of applicability of the chosen expression for the critical Shields parameter includes grain sizes of typical sandy soils. It is therefore also suitable to detect that the soil is stable without scour protection. The approach is not suitable for live sea beds, where transport of the soil doesn’t necessarily mean that a scour hole of significant depth would occur.

The water particle motion is assessed at the seabed, rather than at top-level of scour protection. The latter would be more representative of the velocities at the position of the armour rocks. However, this would lead to an expression for the rock armour
grading that includes the height of the scour protection. This would require an iterative procedure, in which the design of the scour protection and the assessment of shear stresses get updated. It is assumed that the improvement of iteration doesn’t merit the added complexity and computation time for this prototype. The wave conditions for which the shear stress is determined differ from the conditions used by others. For example, Soulsby\textsuperscript{258} suggests to base the characteristic wave height on the root mean square of the wave spectrum and to take the wave period for the peak of the surface elevation spectrum. Similar suggestions are made by den Boon \textit{et al.}\textsuperscript{81}. The used wave conditions simplify the data processing of site conditions.

The $d_{15}$ and $d_{85}$ are not considered to be independent design variables. They are correlated to the $d_{50}$, although this correlation differs for different rock separation processes\textsuperscript{73}. However, the influence that the designer has on this is limited and a common, economic separation process is chosen.

\textbf{Scour protection armour layer thickness}

The thickness of the armour layer is taken to be 2.5 times $d_{50}$ in the region around the pile up to a distance of 1 times the pile diameter. Farther away, a thickness of 1.7 times $d_{50}$ is used. A minimum of 0.3 m is maintained.

These thicknesses are suggested by Halscheple\textit{et al.}\textsuperscript{132}. The larger thickness near the pile is to account for the loss of smaller rocks that may be displaced by wave and current action in the region where water particle velocities are increased by the presence of the pile. The minimum thickness is due to practical matters during installation. The thicknesses are consistent with the statement of De Vos \textit{et al.}\textsuperscript{77} that commonly suggested values range between 2 and 3 times the nominal diameter $d_{n50}$. This nominal diameter is 0.84 times $d_{50}$\textsuperscript{73}. Halscheple\textsuperscript{131} and den Boon \textit{et al.}\textsuperscript{81} suggest thicknesses of 2 and 2.5 times $d_{50}$, respectively.

\textbf{Scour protection filter layer grading}

If there is an armour layer, the $d_{85}$ grading of the filter layers, is determined from:

\[ d_{85,\text{filter},i} = \frac{d_{15,\text{armour}}}{4.5} \text{ and } d_{85,\text{filter},i+1} = \frac{d_{15,\text{filter},i}}{4.5} \quad (i \geq 1) \]  

(4-16)

in which the index $i$ indicates the number of the filter layer, when going from the armour layer down to the seabed. Filter layers are added, as long as the $d_{85}$ of the filter layer is larger than that of the soil. This implies that the number of filter layers may be zero.

Filter layers can have an open geometry or a closed geometry. In open geometries the gaps between the rocks may be large enough to allow base material to pass through, but this doesn’t happen because of the reduced water particle velocities under the filter. According to Halscheple\textsuperscript{131} it appears that geometrically open filters can only be adopted if the protection is mainly subjected to uniform currents. In the present case the main attack is initiated by waves where the reduction in water particle velocities is not obtained.
Halfschepel et al.\textsuperscript{132} and Whitehouse\textsuperscript{306} give a criterion for stability, segregation and permeability of a closed geometry. These criteria imply constraints on the ratios $\frac{d_{15,\text{filter}}}{d_{85,\text{base}}}, \frac{d_{15,\text{filter}}}{d_{15,\text{base}}}$ and $\frac{d_{50,\text{filter}}}{d_{50,\text{base}}}$, in which the index $\text{base}$ designates the base material below the filter layer. For rather uniform materials, CUR/RWS\textsuperscript{73} only provides the constraint on $\frac{d_{15,\text{filter}}}{d_{85,\text{base}}}$. This constraint is the same for all three sources and reads:

\[
\frac{d_{15,\text{filter}}}{d_{85,\text{base}}} \leq 5
\]  

(4-17)

Only this stability criterion is applied, because it needs less soil data to be available. For most materials with narrow or wide grading, where $\frac{d_{85}}{d_{15}} < 2.5$, the other criteria will then also be met. The limiting value of 4.5 is used instead of 5, to accommodate the fact that the filter material that meets the constraint exactly can often not be obtained when standard gradings need to be used. The closer to the limit of the constraint the grading can be chosen, the smaller the rocks in the filter layer and the lower the number of filter layers that are needed.

In practice the filter layers should be stable during the installation of the turbines, when it is not yet protected by the armour layer. This implies that it would be required to resist the annual extreme sea conditions. This requirement has been ignored.

The $d_{15}$ and $d_{50}$ are not considered to be independent design variables. They are correlated to the $d_{85}$, although this correlation differs for different rock separation processes\textsuperscript{73}. However, the influence that the designer has on this is limited and a common, economic separation process is chosen.

**Scour protection filter layer thickness**

The thickness of each filter layer is taken to be 1.7 times its $d_{50}$, with a minimum of 0.3 m.

Similar statements are found as for the thickness of the armour layer. However, the filter layer near the pile doesn’t suffer from the increased water particle velocities around the pile, because it is protected by the armour layer.

**Scour protection diameter**

The diameter of the scour protection is taken to be 6 times the diameter of the monopile.

Halfschepel\textsuperscript{131} identifies four failure mechanisms: erosion of the top layer, loss of seabed material through the protection and shear failure and flow slide at the edge of the protection. The first two are avoided by the rules for the grading and layer thicknesses for the armour and the grading. The latter two failures are acceptable, provided that these end in a stable situation with a downward slope of the armour layer at the edge\textsuperscript{81}. If the final, stable situation with a scour hole around the protection reduces the overburden pressure on the load bearing soil, the monopile would need to be reinforced and extended. This leads to a trade-off between scour protection costs and monopile costs\textsuperscript{132, 288}. However, Halfschepel et al.\textsuperscript{132} mention that this is not a standard method.
and indeed all other consulted sources suggest to apply sufficient protection to avoid any reduction in bearing capacity. Den Boon et al.\textsuperscript{81} and De Vos et al.\textsuperscript{77} suggest that the entire area that would develop a scour hole without protection needs to be covered by rock. The physical basis for this suggestion is poor, since scour protection will create a different flow pattern and will have a different effect on the stability of the surrounding seabed. Halfschepel\textsuperscript{131} suggests that the entire cone of soil that is active in the load transfer of the foundation should be protected. This is very conservative, since the contribution of the outer edge of this cone to stability of the monopile is very small. De Vos et al.\textsuperscript{77} claim that several sources suggest a scour protection diameter of 3 to 5 times the monopile diameter. Since Halfschepel et al.\textsuperscript{132} show that 5 times the diameter is too small if the instability at the edge is considered, a slightly larger diameter is taken.

4.5.3 Electrical infrastructure

\textit{Overview of the algorithm}

Table 4-6 shows the algorithm of the electrical infrastructure design. The burial depths of the cables are determined in advance. Since the winding ratios determine the voltage levels for the transmission and infield cables, these cables are designed inside the transformer loops. The turbine transformer is de facto optimised together with the other two transformers, but its winding ratio can be made dependent on the other winding ratios, as will be explained later. The algorithm for the two cable designs is an alternating formulation of a design with separable constraints. The order in which the two cables are designed is therefore arbitrary. The two cable design processes should be repeated until satisfactory convergence of the objective function has been achieved, but due to the small mutual influence it is sufficient to perform each process only once. The passive shunt reactors are designed inside the transmission cable loop, because they depend on the charging currents of that cable.

\textit{Initial guess}

The design algorithm optimises the winding ratios of the transformers and the cross-sectional areas of the cable conductors. The winding ratio of the transformer determines the voltage ratio between input and output. Given the voltage level at the grid connection point, the total voltage drop over the onshore, offshore and turbine transformer must comply with the nominal generator voltage level at the other end of the electrical system. The initial values of the winding ratios are determined from an initial transmission voltage of 220 kV and an initial infield voltage of 45 kV. For low voltage levels it may be impossible to design a feasible cable, due to the high currents that this brings about. Therefore, the chosen voltage levels are high up in the range of levels observed in realised wind farms. This makes it more likely that feasible cables can be designed for the initial winding ratios.
The conductor diameters of the infield and transmission cables are also optimised in the algorithm and therefore need initial guesses. The rated power capacity of a cable specifies how much current a cable can carry without overheating the insulation material. ABB\(^5\) has calculated ratings of three-core submarine cables with copper conductors according to IEC 60287 series of standards, using predefined conditions for the burial depth of the cable, the temperature of the surrounding soil and seabed thermal resistivity. The ratings given by ABB are independent of the voltage level for which the cable is designed. The independent parameter, diameter of the conductor, \(D_c\) [m], and dependent rated current per phase, \(I_{\text{rated}}\) [A], of the provided data have been reversed. A fit to the result for various cables yielded:

\[
D_c = 33 \cdot 10^{-9} I_{\text{rated}}^2 + 8.9 \cdot 10^{-6} I_{\text{rated}} + 5.7 \cdot 10^{-3} \quad \text{(4-18)}
\]

This equation has been used to make an initial guess of the conductor diameter. As an estimate of the rated current, the current per phase without reactive current and electrical losses has been used. This current follows from the maximum power transported through the cable and its voltage level.

Due to the simplifications in this assessment, it isn’t sufficiently guaranteed that this leads to a feasible cable design. Therefore, this initial guess is suitable to set the initial values for the objective function evaluations in the other disciplines, but it is insufficient as a starting point for the optimisations in this discipline. How this problem is solved is discussed in the design rules below. The other design variables get their initial guess following the design algorithm, for which no evaluation with design variables of other disciplines is needed.

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**Table 4-6 Algorithm of the electrical infrastructure design**

<table>
<thead>
<tr>
<th>Loop</th>
<th>Design variable</th>
<th>Design rule</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission cable</td>
<td>Burial depth</td>
<td>KBE rule</td>
</tr>
<tr>
<td>Infield cable</td>
<td>Burial depth</td>
<td>KBE rule</td>
</tr>
<tr>
<td>Onshore transformer</td>
<td>Winding-ratio</td>
<td>Optimisation</td>
</tr>
<tr>
<td>Offshore transformer</td>
<td>Winding-ratio</td>
<td>Optimisation</td>
</tr>
<tr>
<td>Transmission transformer</td>
<td>Winding-ratio</td>
<td>On constraint</td>
</tr>
<tr>
<td>Transmission cable</td>
<td>Conductor diameter</td>
<td>Optimisation</td>
</tr>
<tr>
<td>Transmission cable</td>
<td>Thickness of:</td>
<td>KBE rule</td>
</tr>
<tr>
<td></td>
<td>- conductor screen</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- insulation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- insulation screen</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- sheath</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- polyethylene sheath</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- binder</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- bedding</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- armour</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- outer serving</td>
<td></td>
</tr>
<tr>
<td>Shunt reactor</td>
<td>Inductance offshore</td>
<td>KBE rule</td>
</tr>
<tr>
<td>Shunt reactor</td>
<td>Inductance onshore</td>
<td>KBE rule</td>
</tr>
<tr>
<td>Infield cable</td>
<td>Cross-sectional area</td>
<td>Optimisation</td>
</tr>
<tr>
<td>Infield cable</td>
<td>Layer thicknesses</td>
<td>KBE rule</td>
</tr>
<tr>
<td></td>
<td>(see transmission cable)</td>
<td></td>
</tr>
</tbody>
</table>
**General simplifications**

The electrical system is very extensive, with cables, transformers, bus bars, switches, protection, reactive power compensation etc. The design algorithm focuses on the components that play a role in the primary function of the system, which is getting the electricity from the turbines to the grid. Important factors in this primary function are voltage levels and active and reactive currents. These factors dominate the design of the cables, transformers and reactive power compensation and vice versa. Therefore, the design algorithm focuses on these components of the electrical system. Each of these components is built up of many elements by itself and therefore has many design variables. Again, design variables are only selected for the algorithm if they are important for the assessment of voltages and currents. This means that the components of the electrical system are characterised by only their governing design variables and that various components are only represented by cost models. As mentioned in the example ad 3.a in Section 4.5.1 the design of the electrical system doesn’t use standard components, to avoid discontinuities in the response of the LPC to input parameters. Instead tailored cables, transformers and reactive power compensation are designed and curve fits to standard solutions have been used to assess the properties of intermediate solutions.

**Discussion of selected design rules**

**Cable burial depths**

The burial depth of the infield cable is chosen to be 1.5 m. The burial depth of the transmission cable is set at 3.0 m.

Schoenmakers\textsuperscript{248} states that typical burial depths of offshore cables are 1.5 m and that the burial depth increases to 3.0 m in a region up to 3 km off the coast. The deeper value is chosen for the transmission cable, because this gives the worst conditions for temperature increase and losses in the cable.

**Transformer winding-ratios**

The offshore wind farm configuration contains a transformer at the grid connection point onshore, one at the offshore platform and one in each turbine. The ratio between the number of windings at the ingoing and outgoing sides of these transformers determine the voltage levels in the cables and at the generator in the turbine. The winding ratios of the onshore and offshore transformer are optimised, while the winding ratio of the turbine transformer is obtained by dividing the overall winding ratio by the winding ratios of both other transformers. The overall winding ratio is set equal to the generator’s nominal voltage divided by the voltage level of the grid at the connection point. The bounds on the onshore transformer ratio are 0.05 – 5.0 and on the offshore transformer ratio they are 0.05 – 1.0. The optimisation of the winding ratios of the two larger transformers is implemented with the sequential least squares programming algorithm of Dieter Kraft\textsuperscript{269}. The winding ratio of the turbine transformer is determined in the inner design loop.

The transformer winding ratios influence the costs and the efficiency of the transformer, but more importantly, they influence the cable costs and losses. Since these contribute
to both numerator and denominator of the LPC, the winding ratios need to be optimised. This optimisation is constraint, because the voltage at the generator needs to be at an effective and allowable level. The voltage levels in the electrical system have been simplified. The voltage level change over the transformer is assumed to be equal to the winding ratio and no voltage drop is assumed over the cables. In this way, the constraint is formulated as an equality constraint that forces the voltage at the generator to be equal to its nominal voltage. The constraint enables an expression of the winding ratio of the turbine transformer as a function of the other transmission ratios. Therefore, the three-variable optimisation is reduced to a two variable optimisation, without constraint.

The bounds on the searched design space for this optimisation are rather critical. Using the previously mentioned assumptions about the voltage levels, the voltage level in the transmission cable follows from the multiplication of the grid voltage with the winding ratio of the onshore transformer. This winding ratio can be larger or smaller than one, considering that the optimal transmission voltage can be larger or smaller than the grid voltage. Particularly when the grid voltage is high, a transmission ratio smaller than one is possibly the optimum. The infield voltage level follows after further multiplication with the offshore winding ratio. The infield voltage level is invariably lower than the transmission voltage level, in practice, and therefore only winding ratios smaller than one are evaluated. The lowest voltage level in the infield cable is obtained when both winding ratios are at the lower bound of their search domain. This lowest voltage level should be below the optimum, in case the onshore grid has a high voltage, but it may not become too low when the onshore grid has a low voltage. When it becomes too low, the currents in the infield cable will become too high to find a feasible cable design. The upper bounds of the winding ratios determine the maximum voltage in the transmission and infield cables. This maximum should be above the optimum voltage level. It has not been investigated whether there is a physical limit on the voltage level that may not be exceeded, because it is not expected that such limit will be exceeded with the chosen upper bounds. The chosen bounds are therefore a balancing act, between including the optimum solution and excluding the possible instability of the algorithm if it runs into a voltage level for which no cable can be designed. For further developments of this algorithm, it is recommended to investigate the use of constraints on estimates of more relevant responses in the cables, such as those of current and voltage levels. This would enable a wider search in the design space for the winding ratios and address the issues more directly.

**Cable conductor diameter**

The cable conductor diameter is optimised. The lower bound of the search area is set at the diameter where the cable reaches the maximum allowed temperature, while the upper bound is set at the diameter where the cable reaches to lowest temperature. For this optimisation the implementation of a bounded minimisation of a scalar function is selected from the Python libraries\(^\text{270}\). The upper bound of the diameter is found by minimising cable temperature in a diameter range of 0.01 times the smallest and 100 times the largest diameter of standard cables from ABB\(^\text{5}\). For this search the same implementation for minimisation of a scalar function is selected. The search for the lower bound is formulated as a root finding problem, by subtracting the estimated temperature in the cable from the maximum temperature. Here, Brent’s algorithm\(^\text{268}\) is chosen to solve this problem. The interval for the tried diameters in this algorithm starts at 0.01 times the smallest diameter of the standard cables and ends at the previously
determined diameter where the minimum cable temperature was obtained. In all previous steps the temperature in the cable is determined at the point with the highest active current and cable charging current. This is at either end of the transmission cable and at the turbine side of the longest infield cable connecting the outer string to the platform, with all turbines operating at rated power.

The temperature in the cable exceeds the temperature of its surroundings, because heat is developed through the electrical losses. The temperature reaches an equilibrium when the conduction of heat balances the heat generation. This temperature becomes a function of the conductor diameter, if the other layers of the cable are known as a function of this diameter. Together with other parameters that are already fixed at this stage, the layout of the cable determines its losses and its heat conductivity. Analysis of these aspects reveals the dependency of temperature in the cable on its conductor diameter. When the conductor diameter is very large, the losses will be small. However, the heat conductivity will also be small, mainly because the thickness of several layers increases with conductor diameter in the design rules for the layer thicknesses. This leads to large temperatures. At first, a decrease in diameter has a larger effect on the heat conductivity than on the losses, and therefore the temperature decreases. At some point, further decrease of the diameter gains a larger effect on the losses than on the heat conductivity and the temperature increases again. The diameter is allowed to decrease, and the temperature is allowed to go up, up to the point where the insulation material deteriorates. This puts a constraint on the temperature, which is translated to a bound in the diameter optimisation.

A slight increase in conductor diameter leads to lower losses, which may outweigh the increase in cable costs. From practical applications it is known that the optimum diameter is at or near the minimum diameter. Therefore, the searched design space is expected to be large enough. The lower bound is chosen to obtain a diameter range where the temperature, the losses and the costs of the cable increase or decrease monotonically. This ensures that the optimisation ends in a global minimum in the search space.

**Cable layer thicknesses**

The thicknesses, $t$, of layers in the cable are taken as function of the cross-sectional area of the conductor, $A_c$, in [m$^2$], the line voltage, $V_L$, in [V] and the diameter, $D$, of other layers in [m]. The indices for the thicknesses follow the names of the layer. The index $c$ is used for the conductor diameter and $is$ for the insulation screen diameter. The used expressions are shown in Table 4-7.

The expressions are determined from analysis of data for standard cables from ABB. The division of the layer thickness for ‘rest of the layers’ over the outer five layers is not supported by data. The thicknesses of the layers need to be implemented as design variables, because the cable geometry determines the cable capacitance and the heat conductivity. These are needed for the temperature assessment.

**Passive shunt reactor inductance**

The design of the reactive power compensation is expressed in the inductance of a passive shunt reactor for each phase, connected to earth. The inductance is actually a
property of this component and not a true design variable. It is assumed that the design of the shunt reactor to achieve this inductance can be done independent of the wind farm design, without leading to trade-offs in the LPC. For both onshore and offshore shunt reactors, the inductance per line, $L$, is determined from:

$$L = \frac{1}{2\pi^2 f^2 C' l}$$ (4-19)

in which:

- $f$ = frequency of the alternating current in the transmission cable,
- $C'$ = capacitance of the transmission cable per unit length,
- $l$ = length of the transmission cable.

With this inductance, half of the charging current of the transmission cable comes from the grid side and half of the charging current comes from the farm side. This gives a symmetric distribution of reactive currents and the lowest values for reactive current that can be achieved with this configuration. Consequently, the temperatures in the cable are lowest with this choice of inductances, which is beneficial for the resistive losses and the constraint on temperature. Furthermore, the symmetric distribution of reactive current leads to the lowest possible losses, because resistive losses are proportional to the square of the current. This is confirmed by Brakelmann\textsuperscript{42}. Schoenmakers\textsuperscript{248} states that offshore compensation is more expensive than onshore compensation, but this effect is neglected.

### 4.5.4 Maintenance

**Overview of the algorithm**

Table 4-8 shows the algorithm of the maintenance design. The amount of working days per week and the duration of the shifts are determined in advance. The number of shifts per day, the number of crews per shift and the waiting time before mobilising lifting equipment when a failure occurred could be optimised in one process. However, their optimisations are nested in three loops, because the first two design variables have

<table>
<thead>
<tr>
<th>Layer</th>
<th>Expression for thickness [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor screen</td>
<td>$t_{cs} = 1.1 \cdot A_c$</td>
</tr>
<tr>
<td>Insulation</td>
<td>$t_i = 83 \cdot 10^{-9} \cdot V_L + 4.0 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>Insulation screen</td>
<td>$t_{is} = 0.016 \cdot D_c + 1.0 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>Sheath</td>
<td>$t_s = 0.035 \cdot D_s + 0.2 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>Rest of the layers</td>
<td>$t_{rest} = 0.17 \cdot D_s + 19 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>Polyethylene sheath</td>
<td>$t_{ps} = 0.05 \cdot t_{rest}$</td>
</tr>
<tr>
<td>Binder</td>
<td>$t_{bi} = 0.05 \cdot t_{rest}$</td>
</tr>
<tr>
<td>Bedding</td>
<td>$t_b = 0.3 \cdot t_{rest}$</td>
</tr>
<tr>
<td>Armour</td>
<td>$t_a = 0.3 \cdot t_{rest}$</td>
</tr>
<tr>
<td>Outer serving</td>
<td>$t_{os} = 0.3 \cdot t_{rest}$</td>
</tr>
</tbody>
</table>
discrete options. The latter is a continuous variable, which can be optimised with gradient-based methods. The number of access vessels is made dependent of the number of crews in a shift.

**Initial guess**

The design algorithm optimises the number of shifts per day, the number of crews per shift and the waiting time before ordering lifting equipment after a failure occurred that needs it. In the initial setting, the waiting time before ordering lifting equipment is set at zero. The initial number of shifts per day is one, meaning that maintenance is only performed during daytime.

For the number of crews per shift, two constraints are formulated. After a period of inaccessibility due to storm, a waiting list for repairs has developed. For an average storm length and average length of the period until the next storm, the number of crews must at least be sufficiently large to clear this waiting list. This constraint is enforced because it is an assumption in the model that is used, but it is also a realistic requirement. If it is not met, the number of failed turbines may diverge to unacceptably high numbers. The same holds true for the second constraint, which requires that the number of crews is at least large enough to do all preventive maintenance in periods when some crews have no repairs to do. Having set all other design variables, these two constraints are evaluated and the initial guess for the number of crews is the lowest value that meets both.

**General simplifications**

A fixed strategy of deployment of crews and a predefined order in which turbines are repaired is chosen as presented in Table 4-3. An equal number of crews is chosen for all shifts, although it might be better to have more crews working during the day, when personnel costs are lower than during the night. Optimisation of crew deployment on a day-to-day basis, given the actual status of the wind farm and the weather, could increase the availability and improve the efficiency of crew deployment. However, the effect of such optimisation is simplified by assuming a crew deployment efficiency of 90%.

All design variables that are considered in the optimisation of maintenance influence both numerator and denominator of the LPC, through maintenance costs and through availability. Therefore, they are either optimised, or an estimate is made for their optimum value.

<table>
<thead>
<tr>
<th>Loop</th>
<th>Design variable</th>
<th>Design rule</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shift</td>
<td>Working days per week</td>
<td>KBE rule</td>
</tr>
<tr>
<td>Shift</td>
<td>Duration</td>
<td>KBE rule</td>
</tr>
<tr>
<td>Shift</td>
<td>Number per day</td>
<td>Optimisation</td>
</tr>
<tr>
<td>Shift</td>
<td>Number of crews</td>
<td>Optimisation</td>
</tr>
<tr>
<td>Access vessels</td>
<td>Number of vessels</td>
<td>KBE rule</td>
</tr>
<tr>
<td>Lifting equipment</td>
<td>Waiting time before mobilisation</td>
<td>Optimisation</td>
</tr>
</tbody>
</table>
Discussion of selected design rules

Working days per week and shift duration
The number of working days per week is set at 7 and the duration of the shift is set at 12 hours.

A workweek of 7 days is assumed to simplify the model for the analysis of maintenance performance. However, it is also expected that it is optimal to spread the deployment of crew equally over the week, to avoid long downtimes of turbines while there are no shifts. This does require sufficient personnel to cover the whole week, which may lead to sub-optimal occupancy rate of personnel for small wind farms.

The duration of the shift is set at a high value to achieve a high effective working time in the turbines, relative to the travel time to and in the farm. The chosen value is representative for the maximum under labour regulations. This bound acceptable point is expected to be the optimum value, although it leads to a low occupancy rate of personnel for small wind farms.

Number of shifts per day
The number of shifts per day is optimised. The number of shifts is either one or two.

It is chosen to have no overlap between shifts, even though this may not be the optimal solution. With a shift duration of 12 hours, this means that there can be only one or two shifts per day. Both options are evaluated and the one with the lowest LPC is chosen.

Number of crews per shift
The number of crews per shift is optimised. The starting point for the optimisation is the minimum number of crews that is described in the initial guess. This minimum depends on the number of shifts per day. The number of crews per shift is increased until LPC starts to go up, at which point the previous number of crews is chosen as the optimum value.

When LPC starts to go up, the increase in personnel costs outweighs the increase in availability. Since the increase in personnel costs will continue at the same rate, while the increase in availability levels off, it is reasonable to expect that LPC will not reduce anymore for larger numbers of crew per shift.

Number of access vessels
The number of access vessels is set at the minimum that is required to transport all personnel of one shift to the wind farm at the same time.

When less access vessels are used, some crews have to wait until a vessel returns from an up and down trip to the wind farm to drop off the other crews. It is expected that deployment of personnel without delay generally outweighs the saving in vessel costs. Once inside the wind farm, crews have to be brought to their turbine in order. When more vessels are used, crews have to wait less for other crews that are being transported inside the wind farm. Since travel times inside the wind farm are usually smaller than
travel times from the harbour to the wind farm, it is expected that further optimisation of
the number of vessels to mitigate this waiting time will have limited effect on LPC.

A more optimal deployment of access vessels might have been obtained if not all crews
started their shift at the same time, but as mentioned before it was chosen not to allow
overlap in shifts.

**Waiting time before mobilisation of lifting equipment**
The waiting time before mobilisation of lifting equipment is the time between the
occurrence of a failure that needs the equipment and the time that the equipment is
ordered. The longer this waiting time, the higher the downtime of the failure, but the
higher the probability that another failure will occur that needs lifting. If one or more
extra failures occur, the lifting equipment is deployed more effectively, because then it
repairs more failures per mobilisation. This waiting time is optimised, with a lower
bound of zero hours and an upper bound of a full year of 8760 hours.

Since there are no constraints in this optimisation, the implementation of a bounded
minimisation of a scalar function is selected from the Python libraries.

### 4.5.5 Layout

**Overview of the algorithm**
Table 4-9 shows the algorithm of the layout design. The spacing in the rows and
columns are optimised, while the position of the platform relative to the positions of the
wind turbines is determined with a straightforward algorithm.

**Initial guess**
The initial guess for the spacing is 7 times the rotor diameter in both directions. This
spacing is observed in Horns Rev I and similar spacing can be observed in other
offshore wind farms. Since there is no constraint on the area that can be occupied by the
wind farm, as will be discussed in the general simplifications, this initial guess is a
feasible design.

**General simplifications**
In an actual wind farm development many factors affect the objective function and the
constraints of the layout optimisation. The boundary of the available area is usually
fixed and inside the area there may be restrictions due to for instance pipes, cables and
unsuitable soil conditions. The variation in water depth and soil conditions affects the
support structure costs. The wind speeds are not uniformly distributed over the wind
directions, which affects the array efficiency. The orientation of the area with respect to

<table>
<thead>
<tr>
<th>Loop</th>
<th>Design variable</th>
<th>Design rule</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine locations</td>
<td>Spacing inside row</td>
<td>Optimisation</td>
</tr>
<tr>
<td>Turbine locations</td>
<td>Spacing inside column</td>
<td></td>
</tr>
<tr>
<td>Turbine locations</td>
<td>Location with respect to platform</td>
<td>KBE rule</td>
</tr>
</tbody>
</table>

Table 4-9 Algorithm of the layout design
the direction to the grid connection point influences the lengths of both infield and transmission cables.

Many of these conditions are very site specific. To include them in the optimisation algorithm would require of the user to choose these site specific conditions and it would make the LPC dependent on this choice. However, the turbine is designed for a variety of sites that are not known in advance. Therefore, it is chosen to ignore constraints that have a large variation over different sites. This includes foremost the geometrical description of the available positions for wind turbines. A more general restriction on the available area has been considered, such as a cap on the surface or a rectangular boundary. However, this constraint should in some way be in agreement with the number of turbines that can be varied by the user. Since no guideline could be formulated how this agreement could be achieved in a manner that is useful for this prototype, no constraint on available area has been implemented.

The orientation of the array of wind turbines with respect to area, the prevailing wind and the directions to the grid connection point and the harbour are also considered to be fairly site specific. Therefore, the orientation is not optimised. To avoid that this fixed orientation doesn’t match the distribution of wind directions a uniform distribution is implemented.

**Discussion of selected design rules**

**Spacing between turbines**

The spacing between the rows and the columns is optimised, without constraints. To facilitate the additions of constraints in the future, the optimisation is also implemented with the sequential least squares programming algorithm of Dieter Kraft. The search area is limited between 1 time the rotor diameter to 25 times the rotor diameter spacing in both directions.

Variation of spacing influences both numerator and denominator of the LPC, through cable costs, array efficiency and efficiency of the electrical system. The consequence of these opposing effects cannot be known a priori and therefore an optimisation chosen. The decision to not implement constraints is discussed in the previous section. Practical experience indicates that the searched design space should include the optimum spacing.

**Position of platform relative to turbines**

The offshore platform is positioned in the middle of the rows with a separation distance from the outmost column of 100 m.

The position of the offshore platform often deviates from this definition in realised wind farms. This deviation relates mostly to the orientation of the array relative to the grid connection point and restrictions on cable routes. Since such specific conditions are ignored, these deviations are not considered and the offshore platform position is chosen to give the lowest infield cable length.
4.6 Cost models

4.6.1 Generic modelling aspect

Timing of expenses and production
All investment costs are assumed to be made in year zero, which is the year before first production. Annual operation and maintenance costs as well as the annual energy yield are assumed to be constant over the lifetime of the wind farm, up to and including the last year of the wind farm’s lifetime of 20 years. All decommissioning costs are assumed to be made in that same last year.

Inflation and exchange rates
Kaiser and Snyder provide the average inflation in zones with different currencies over the 10 year period from 2000 to 2009. The quarterly exchange rates from various currencies to Euro have been taken from AONDA for the period October 2011 – December 2011. These inflation and exchange rates are presented in Appendix C and are used to express all costs on the same reference date and in the same currency. The reference date can be changed in the tool, since all cost models are stored in their original currency and with their own reference date.

There are several known omissions in this model. For instance, the same inflation rate is applied to all products and services, while in reality each of them will have a different inflation rate. The exchange rate is applied for a fixed date, although it would need to be applied on the date of the money transfer. A final example of inaccuracy in the model is that the currency in which costs or a cost model are presented in literature may not be the currency of the original data. This means that the applied inflation rate may not be appropriate and that an exchange rate may have been applied that is inconsistent with the current model. These omissions in the model may affect the absolute outcome of the cost evaluations, but they are expected to have little effect on the trends in LPC. Since these trends are the dominant outcome of the tool, this simple model is considered to be acceptable. Furthermore, improvements of this model are unlikely to be very effective, since the underlying costs and cost models already contain large uncertainties and natural variation.

Choice of independent variables
Many cost models in literature are functions that are determined empirically. Cost data is collected and presented as a function of independent parameters, after which a function is fitted through the data. The choice of the independent parameters and the type of function can be based on a reasoned dependency, but it can also be based on an observed or perceived correlation. The last approach doesn’t always lead to a cost model that properly presents the causal effects. For instance, Milborrow presents bottom lease charges as a function of energy yield. This is clearly not based on a direct causal relation between the two, but on the correlation of energy yield to the size of the area that is used by a wind farm. For the cost models that are used in the tool, it is tried to use the most fundamental independent parameters, because it is important that the model captures the causal effects. Otherwise, the way in which variation of the design variables affects the LPC is not properly represented, and the wrong parameters get
focus in the optimisation. Returning to the previous example, optimisation with the expression of Milborrow would have no effect at all on the point where minimum LPC is obtained, since LPC is multiplied with a constant factor for all design solutions. However, with a more realistic expression the optimisation would tend to slightly smaller spacing. In several cases, such as the one described above, other independent parameters are chosen than the ones in the original models. The new model is then calibrated with some sample points of other models, possibly supplemented with other data.

4.6.2 Overview of all cost models

Table 4-10 through Table 4-13 present information about the cost models that are used in the tool. The tables show on which variables of the tool the costs depend and which principles are used in the modelling process. The modelling processes for cable costs, transformer costs and offshore platform costs are too extensive to describe in the tables. Therefore, these are described in the next section. The mathematical formulations of the models and the currency and year for which they represent the costs are given in Appendix C.

Some cost models are more heuristic than others. For instance, consumable costs for repairs are determined from first principles, while installation costs of the measuring tower is just a fixed value. This fixed value implicitly represents the outcome of the whole design process for the measuring tower, including its optimisation and fulfilment of constraints. This design process entails many more design variables that are not modelled in the tool. Highly heuristic cost models are used for all ‘other components and procedures’ in Figure 4-10. Similarly, design variables of the manufacturing process of the tower are only implied by the cost model, since these are represented by the costs per kilogram steel. On the other hand, the structural design variables of the tower explicitly affect the costs, as these are represented in the model by the tower mass. The choice of having an explicit role of design variables in the optimisation in the tool or an implicit role in a heuristic cost model depends on how well either is expected to capture the sensitivity to rotor-nacelle properties, site conditions and farm size. This choice is mainly made on engineering intuition that is based on past experience and discussions in literature. Since most of the cost models used in the tool depend on more variables than the cost models found in literature, it is expected that the sensitivity of the costs at least exceeds the state of the art in cost modelling for offshore wind farms.
Table 4-10 Independent variables and modelling approach for investment costs for hardware (procurement)

<table>
<thead>
<tr>
<th>Cost component</th>
<th>Independent variables</th>
<th>Modelling approach</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rotor-nacelle</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Purchase</td>
<td>Number of turbines - RNA purchase price</td>
<td>Purchase price per rotor-nacelle assembly assumed independent of magnitude of the sale</td>
</tr>
<tr>
<td>Warranty</td>
<td>Number of turbines - RNA purchase price - Warranty percentage</td>
<td>Warrant costs per rotor-nacelle assembly assumed independent of magnitude of the sale</td>
</tr>
<tr>
<td><strong>Support structure</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tower</td>
<td>Number of turbines - Tower mass</td>
<td>Several sources\textsuperscript{\textsuperscript{19, 105, 111}} model tower costs as linear function of mass - The coefficients of Fingersh \textit{et al.} \textsuperscript{111} for steel, labour and marinisation are copied - Large variation in steel prices over the years are ignored - A 20% surcharge is added for secondary steel in the tower.</td>
</tr>
<tr>
<td>Transition piece</td>
<td>Number of turbines - Transition piece mass</td>
<td>Similar to tower costs assumed to be a linear function of mass - Coefficient based on analysis of information from Mast\textsuperscript{197}</td>
</tr>
<tr>
<td>Boat landing</td>
<td>Number of turbines</td>
<td>Copied\textsuperscript{111}</td>
</tr>
<tr>
<td>Grout</td>
<td>Number of turbines - Grout mass</td>
<td>Similar to tower costs assumed to be a linear function of mass - Coefficient based on some generic information about concrete</td>
</tr>
<tr>
<td>Monopile</td>
<td>Number of turbines - Monopile mass</td>
<td>Similar to tower costs assumed to be a linear function of mass - Coefficient based on several sources\textsuperscript{88, 105, 197}</td>
</tr>
<tr>
<td>Scour protection</td>
<td>Number of turbines - Volume of scour protection</td>
<td>Analysis of data\textsuperscript{132} shows a near linear dependency on volume - Fixed costs for installation are neglected – Halschespehl \textit{et al.} \textsuperscript{131} give similar coefficient – A more detailed model is possible\textsuperscript{166} (e.g. including distance to harbour), but the role of these costs doesn't merit that.</td>
</tr>
<tr>
<td><strong>Electrical system</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Infield cable</td>
<td>Conductor mass - Insulation mass</td>
<td>See Section 4.6.3</td>
</tr>
<tr>
<td>Transmission cable</td>
<td>Conductor mass - Insulation mass</td>
<td>Same as infield cable</td>
</tr>
<tr>
<td>Reactive power</td>
<td>Shunt reactor power onshore and offshore</td>
<td>Follows suggestion of Lundberg\textsuperscript{192} that costs are about 2/3 of transformer costs of equal power. High power transformer model used, with voltage ratio of 1.</td>
</tr>
<tr>
<td>Transformer</td>
<td>Number of turbines - Rated power - Voltage ratios of transformers</td>
<td>See Section 4.6.3</td>
</tr>
<tr>
<td>Switch gear</td>
<td>Number of rows - Number of columns - Voltage levels in infield and</td>
<td>Cost per cubicle modelled according to Lundberg\textsuperscript{192} - Model from Elkinton\textsuperscript{105} is similar, but not as clearly defined for what it can be used - Data of Dicorato \textit{et al.} \textsuperscript{88} is not</td>
</tr>
<tr>
<td>Cost component</td>
<td>Independent variables</td>
<td>Modelling approach</td>
</tr>
<tr>
<td>----------------</td>
<td>----------------------</td>
<td>--------------------</td>
</tr>
<tr>
<td>Management</td>
<td>Total decommissioning costs</td>
<td>Assumed to be percentage of total costs. Percentage taken within range of data.</td>
</tr>
<tr>
<td>Removal</td>
<td>Rotor-nacelle assemblies</td>
<td>Number of turbines - Hub height</td>
</tr>
<tr>
<td></td>
<td>Foundations</td>
<td>Number of turbines - Monopile mass</td>
</tr>
<tr>
<td></td>
<td>Infield cable</td>
<td>Length of infield cable</td>
</tr>
<tr>
<td></td>
<td>Transmission cable</td>
<td>Length of transmission cable</td>
</tr>
<tr>
<td></td>
<td>Offshore platform and measuring tower</td>
<td>(Fixed value)</td>
</tr>
<tr>
<td></td>
<td>Scour protection</td>
<td>Number of turbines - Volume of scour protection</td>
</tr>
<tr>
<td></td>
<td>Site clearance</td>
<td>Number of turbines</td>
</tr>
<tr>
<td>Disposal</td>
<td>Rotor-nacelle assemblies</td>
<td>Number of turbines - Mass of rotor-nacelle</td>
</tr>
</tbody>
</table>

**Table 4-11 Independent variables and modelling approach for decommissioning costs**

<table>
<thead>
<tr>
<th>Cost component</th>
<th>Independent variables</th>
<th>Modelling approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measuring tower</td>
<td>(Fixed value)</td>
<td>Expert opinion</td>
</tr>
<tr>
<td>Onshore premises</td>
<td>(Fixed value)</td>
<td>Expert opinion</td>
</tr>
<tr>
<td>Offshore platform</td>
<td>Number of turbines - Rated power - Water depth</td>
<td>See Section 4.6.3</td>
</tr>
</tbody>
</table>

Auxiliary

- Measuring tower (Fixed value): Expert opinion
- Onshore premises (Fixed value): Expert opinion
- Offshore platform: Number of turbines - Rated power - Water depth

See Section 4.6.3
<table>
<thead>
<tr>
<th>Cost component</th>
<th>Independent variables</th>
<th>Modelling approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Management</td>
<td>Total investment costs</td>
<td>Assumed to be percentage of total costs. Percentage taken within range of data from Dicorato et al.(^\text{88})</td>
</tr>
<tr>
<td>Engineering</td>
<td>Number of turbines - Rated power</td>
<td>Copied(^\text{111})</td>
</tr>
</tbody>
</table>

### Installation – Foundations

| Foundations | Number of turbines - Monopile mass | Several sources\(^\text{88}, 105\) model these costs as linear function of monopile mass - Coefficient is determined from analysis of their models and additional data\(^\text{35}, 166\) |

### Installation – Rotor-nacelle assembly

| Offshore works | Number of turbines - Hub height | Cost of lifting assumed to depend on hub height and RNA mass, but collected data was insufficient to model mass dependency - Collected dayrates for lifting equipment showed linear dependency on hoisting height - This dependency is multiplied with a constant factor to represent the number of working days and the other costs of the offshore works - The multiplication factor is calibrated with data from an example\(^\text{166}\) |

### Installation – Electrical system

| Infield cable | Length of infield cable | Expressing as linear function of cable length is common, sometimes separating fixed costs\(^\text{124}, 166, 193, 219\). Models and data of these sources analysed and fixed costs of Nielsen\(^\text{219}\) and variable costs from an example of Kaiser and Snyder\(^\text{166}\) match best with current cost breakdown. Cable tie-in costs not modelled separately, for lack of information, but assumed to be included in variable costs. |
| Transmission cable | Length of transmission cable | Same as for infield cable laying |

### Installation – Auxiliary

<table>
<thead>
<tr>
<th>Dune crossing</th>
<th>(Fixed value)</th>
<th>Expert opinion</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Measuring tower</th>
<th>(Fixed value)</th>
<th>Expert opinion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harbour use</td>
<td>Number of turbines - Rated power</td>
<td>Port and staging costs(^\text{111}) interpreted as harbour use</td>
</tr>
</tbody>
</table>

---

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<table>
<thead>
<tr>
<th>Cost component</th>
<th>Independent variables</th>
<th>Modelling approach</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Management</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total O&amp;M costs</td>
<td>Assumed to be percentage of total costs. Percentage taken within range of data(^\text{86})</td>
<td></td>
</tr>
<tr>
<td><strong>Consumables for repairs</strong></td>
<td>Number of failures - Consumable costs per failure</td>
<td>Summation of costs per failure</td>
</tr>
<tr>
<td><strong>Consumables for preventive maintenance</strong></td>
<td>Number of PM visits - Consumable costs per PM visit</td>
<td>Summation of costs per visit</td>
</tr>
<tr>
<td><strong>Access vessels</strong></td>
<td>Number of vessel rental hours</td>
<td>Summation of costs per vessel rental hour - Typical dayrate(^\text{166}) converted to hourly rate assuming 50% usage ratio.</td>
</tr>
<tr>
<td><strong>Personnel</strong></td>
<td>Number of people per crew - Number of crews per shift - Number of shifts per day - Shift duration</td>
<td>Summation of costs per personnel deployment hour, with higher wages after the 8th hour in the shift and an increase in wage when working in shift rotation. Wages from expert opinion.</td>
</tr>
<tr>
<td><strong>Lifting equipment rental</strong></td>
<td>Number of hours used - Number of mobilisations - Hub height</td>
<td>Summation of mobilisation costs and cost for all hours that equipment is used - Dayrates of lifting equipment and other vessels in the spread(^\text{166}) combined with the approach for RNA installation to estimate and hourly rate as a function of hub height, assuming a usage ratio of 20/24. Average mobilisation time of 48 hours assumed for dedicated turbine maintenance vessels.</td>
</tr>
<tr>
<td><strong>Subsea inspection</strong></td>
<td>Number of turbines</td>
<td>Expert opinion for farm translated to a per turbine value</td>
</tr>
<tr>
<td><strong>Operation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Insurance</strong></td>
<td>Number of turbines - RNA purchase price</td>
<td>Assumed to be a percentage of purchase price - Milborrow(^\text{202}) gives insurance costs per energy yield and average turbine costs per rated power. Estimating average energy yield per rated power, this is translated to turbine costs per energy yield. This gives three estimates of insurance costs as percentage of turbine costs, of which the middle is taken.</td>
</tr>
<tr>
<td><strong>Grid charge</strong></td>
<td>Annual energy yield</td>
<td>Copied(^\text{202}) - Insufficient information to judge whether it would be better to model as function of installed capacity.</td>
</tr>
<tr>
<td><strong>Bottom lease</strong></td>
<td>Area used</td>
<td>May actually not apply at many locations, but represents a burden on space used in such cases. Therefore, taken as a linear function of area used. Lease charges per energy produced taken from Milborrow(^\text{202}), translated to costs per square meter using estimates for energy yield and area used for Horns Rev I.</td>
</tr>
<tr>
<td><strong>Administration</strong></td>
<td>(Fixed value)</td>
<td>Expert opinion</td>
</tr>
</tbody>
</table>

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4.6.3 Detailed description of several cost models

**Cables**

Several models or data of cable costs exist, that express costs as a function of voltage, rated current, transported power, or a combination of these. Green et al.\textsuperscript{[124]} tabulate costs as a function of conductor cross-sectional area and voltage. However, none of these models uses the detailed information of the cables that is available from the engineering models in the tool.

It is assumed that cable costs can be expressed in the amount of copper and insulation material that is used. These two materials are expected to have the highest raw material costs of the cable and they represent current carrying capacity and voltage breakthrough resistance, respectively. Therefore, the initial assumption is that costs can be determined from the cable dimensions, using a price per mass of copper, a price per mass of XLPE, a surcharge factor on these material costs for manufacturing and other materials and an offset.

To obtain the coefficients of the model, it has been calibrated with the model of Lundberg\textsuperscript{[192]}. This is the most extensive of the reviewed models. Furthermore, Lundberg’s model has been validated with data of many existing cables and it compares well with the data of Green \textit{et al.}\textsuperscript{[124]} and the graphs of Nielsen\textsuperscript{[219]}. The procedure for the calibration is the following:

- Current ratings of cables from ABB\textsuperscript{[5]} are determined as function of cross-section
- Cable designs are made with the engineering model in the tool with different cross-sections and different voltage levels
- Copper mass and XLPE mass are determined for these cables
- Price according to Lundberg’s model\textsuperscript{[192]} is determined as function of cable current rating and voltage
- A curve fit is made of price versus copper and XLPE mass

**Transformers**

Reviewed cost models for transformers give costs as function of power only, although an indication of the voltage level is given for which the costs apply. Günther\textsuperscript{[128]} gives cost data of transformers and states their power and the voltage levels on both sides. These costs show scatter as a function of the power. However, when groups of transformers are taken that have the same voltage ratio, the cost data lies on lines of increasing costs with increasing ratio. This is not unexpected, since higher costs would be associated with the battle against higher losses that tend to occur at higher voltage ratios. It is preferred to include this phenomenon in the cost model, since it will impact the effect that infield voltage level has on the trade-off between turbine transformer costs and infield cable costs and losses. A preliminary run of the tool without a cost penalty for higher voltage ratios resulted in infield voltages of over 50 kV for the Horns Rev I wind farm, which is much higher than the realised voltage level. The tool enables the use of a more precise model, since the voltage ratios are known from the engineering model.
The data of Günther\textsuperscript{128} is used to fit the costs as function of voltage ratio. However, the absolute values of the costs according to Günther are much higher than those of all the other sources. Therefore, the model for the voltage ratio is combined with the model that Dicorato \textit{et al.}\textsuperscript{88} have taken from Lazaridis\textsuperscript{186} for medium and high voltage transformers. The combined model is calibrated for a voltage ratio of 4, which is typical for high voltage transformers. For lower voltage levels the model of Bulder \textit{et al.}\textsuperscript{49} is combined with the model for the voltage ratio. This combined model is calibrated for a voltage ratio of 50, which is typical for turbine transformers. The original low voltage and medium to high voltage models correspond at 16 MW, so this is used as the transition point between the models.

\textbf{Offshore platform}

The mass of the topside of the offshore platform is expressed as a linear function of the rated capacity of the wind farm, as obtained from a curve fit to data from Kaiser and Snyder\textsuperscript{166}. The data for the platform of the Lincs wind farm is ignored, because this has an exceptionally heavy topside. Kaiser and Snyder also give an empirical expression for the mass of the jacket as a function of the topside. Substituting the linear curve fit into this expression yields a jacket mass as a function of water depth and farm rated power.

Lundberg\textsuperscript{192} gives a linear model of costs as a function of farm rated power. This model is for a sophisticated platform with living quarters for workers. This is not appropriate for the chosen maintenance procedures. After comparison of results of this cost model with data from others\textsuperscript{88, 124, 219}, the costs are multiplied with 2/3 to make them representative for a platform without accommodation.

Combining the previous two models enables to plot jacket mass in 25 m water depth and costs as a parametric function of rated power. A curve fit to this plot expresses costs as a function of jacket mass. This approach makes costs a function of both water depth and farm rated power. This cost model includes the costs of installation.

\section*{4.7 Physical models for constraint and objective function}

\subsection*{4.7.1 Introduction}

Several physical properties and responses of the system are used in the evaluation of constraints and the objective function. These parameters are functions of the rotor-nacelle properties, the site conditions, the farm size and the design variables of the tool. As stated in the general considerations of Section 4.5.1 the models for these parameters should be simple, yet capture the sensitivity to the input parameters. Various models are selected from literature and could directly be applied. Some models have been further developed, to get more useful expressions. For instance, for all loads analytically integrated expressions are derived to avoid time consuming numeric integration. Furthermore, some elementary models are applied in specially derived algorithms, to create models for more comprehensive systems. This is for instance the case for the evaluation of array efficiency and of the electrical system. For the evaluation of maintenance an entirely new model is developed. The reasons to develop a new model are given in the section that describes the model.
To avoid lengthy texts, many descriptions of the models use jargon, which is considered to be known to readers that are familiar with the domain that is discussed. Other readers should refer to the references to understand the jargon. Trivial models are not discussed and no references are given for models that are so common that they can be found in many sources. Mathematical descriptions of the models are given in Appendix D.

### 4.7.2 Site conditions

The conditions of the site are specified by the user with several characterising parameters. Some models need more detailed parameters than are provided in the user input. Table 4-14 shows which parameters are derived and with which models.

### 4.7.3 Gravity loading

Gravity loading is determined in a straightforward way, using analytical expressions for the tapered tower segments and uniform transition piece and monopile. The gravity force and moment caused by the rotor-nacelle assembly follow from the inputs for its mass and mass eccentricity.

### 4.7.4 Aerodynamic loading

To determine the force and moment on the tapered tower in wind shear a constant drag coefficient is assumed. The drag force is integrated analytically from the top of the

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Modelling principle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual average wind speed</td>
<td>From Weibull distribution</td>
</tr>
<tr>
<td>Reference wind speed</td>
<td>5 times annual average wind speed</td>
</tr>
<tr>
<td>Extreme gust</td>
<td>1.2 times reference wind speed</td>
</tr>
<tr>
<td>Reduced gust</td>
<td>1.2/1.1 times reference wind speed</td>
</tr>
<tr>
<td>Wind shear profile</td>
<td>Power law</td>
</tr>
<tr>
<td>Extreme wave height</td>
<td>1.86 times significant wave height, with maximum at breaking wave limit</td>
</tr>
<tr>
<td>Reduced wave height</td>
<td>1.32 times significant wave height, with maximum at breaking wave limit</td>
</tr>
<tr>
<td>Period of a wave</td>
<td>Correlated to wave height</td>
</tr>
<tr>
<td>Peak period</td>
<td>1.4 times the zero-crossing period (for a peak enhancement factor of 1)</td>
</tr>
<tr>
<td>Wave number</td>
<td>Solving the dispersion relation with an implementation of Newton-Raphson, starting with the deep water solution</td>
</tr>
<tr>
<td>Amplitude of bottom orbital motion and velocity</td>
<td>Determined with linear Airy wave theory</td>
</tr>
<tr>
<td>Crest and trough of extreme wave</td>
<td>Respectively 0.55 times the wave height above MSL and 0.45 times the wave height below MSL</td>
</tr>
<tr>
<td>Increase of current velocity around monopile</td>
<td>1.5 times the undisturbed velocity. Potential flow gives a velocity increase of 2, but the increase reduces rapidly with distance to the pile.</td>
</tr>
<tr>
<td>Increase of wave water particle velocity due to horse shoe vortex around monopile</td>
<td>No increase for small Keulegan-Carpenter (KC) and transition to double the velocity around KC=6. The transition is made gradual, to avoid discontinuous response in the optimisation.</td>
</tr>
</tbody>
</table>
tower to the height at which the force is desired, using the power law for the wind shear. The moment is obtained by integration of the drag force times the lever arm to the desired height. If the force or moment is required below the tower base, the integration is performed down to the base. The obtained expressions for force and moment are also valid for the transition piece above the water level. The expressions have been verified by comparison with numerically integrated results for several cases.

The aerodynamic loads on the rotor-nacelle assembly are entered by the user for operational wind speeds. For idling conditions the aerodynamic loads are determined from the drag coefficients of the nacelle and the rotor, such that they can be determined as function of extreme wind speed and hub height.

4.7.5 Hydrodynamic loading
To determine the force and moment on the submerged part of the transition piece and on the monopile the water particle velocities are modelled with a linear Airy wave and the drag and inertia force are modelled with Morison’s equation. This is a common approach for the analysis of support structures with monopiles, although for larger waves non-linear models are used in accurate analyses. The implementation of non-linear models is an extensive task and although the current approach will not give accurate results, it is expected to capture the relevant effects of wave loading. The amplitudes of the drag and inertia force are analytically integrated over the height of the relevant uniform cylinder. The moments are determined by integration of the load amplitude multiplied with the lever arm to the height at which the moment is desired. Drag coefficient and inertia coefficient are assumed to be constant over the height of integration. Because the maximum drag load and the maximum inertia load do not occur at the same phase of the wave, the combined effect is approximated by taking the root summed squares of the two.

The analytic expressions have been checked by substituting integration from the seabed to sea level. This yields the same expressions for loads and moments on a uniform cylinder at the mudline as those from Vugts et al. Furthermore, the expressions have been verified by comparison with numerically integrated results for several cases.

4.7.6 Mechanics
For the stress analysis in the monopile only longitudinal stresses are considered. Since the loading configuration can be characterised as a cantilever beam with most of the loading at the end, it is reasonable to neglect the effect of shear stresses. The total stress is determined as the summation of the stress due to axial loading and the maximum stress due to bending. Stresses in the tower and transition piece are determined according to the guidelines of Det Norske Veritas, so that they represent both the effect of yield and of buckling. Following the same guidelines, the Euler buckling analysis is performed assuming a uniform diameter and wall thickness over the full height of the support structure.

4.7.7 Geophysics
The clamping depth of the monopile is determined by solving Blum’s expression for laterally loaded piles in uniform cohesionless soil. Blum’s model gives a relation
between clamping depth of the pile and the lateral force and moment at the pile top. Since this is an implicit relation, it is rewritten as a root finding problem. The interval for the tried clamping depths is fixed to 0.1 – 1000 m, which by comparison to observed penetration depths of monopiles is expected to be wide enough. The assessed function is monotonically increasing and is therefore solved with Brent’s root finding algorithm for sign changing intervals.

4.7.8 Rocks

d_{15} and d_{85} are related to d_{50} for the armour layer and d_{15} and d_{50} are related to d_{85} for the filter layers with linear expressions. The expressions are based on analysis of data and various relations between other bulk properties of rock, such as distributions of volume and weight. Available data of other parameters are translated to d_{15}, d_{50} or d_{85}. These translations use either geometric relations, e.g. between volume and diameter for an assumed rock shape, or correlations, e.g. between minimum rock dimension and sieve size. Data and relations are taken from CUR/RWS and Halfschepel. For armour rock data are analysed for standard heavy gradings and for the filter layers data for standard fine and light gradings are used.

4.7.9 Hydrology

For the critical Shields parameter an expression is chosen from Soulsby and Whitehouse. There are various other mathematical descriptions for the critical Shields parameter, which cover different ranges of grain sizes. The chosen expression covers a very wide range, making it suitable for a large variety of gradings of riprap as well as for grain sizes of typical sandy seabed soils.

The characteristic shear stress on the armour rock is determined for the combined effect of current and waves. The combination of the independent shear stresses is done according to Soulsby and Whitehouse. CUR/RWS and De Vos et al. give alternative expressions for the combination of stresses, but these appear to be less advanced and do not include the angle between current and waves.

The shear stress due to current follows a model by Whitehouse. Several sources give an alternative for the drag coefficient, which is expressed as a function of the Chézy coefficient, but that expression appears more suitable for current shear stress in river beds.

The shear stress due to waves is expressed in the wave friction factor. The determination of the wave friction factor follows one of the procedures suggested by Soulsby. The friction factor for rough beds and smooth beds are determined and the larger of the two is taken. The smooth bed friction factor has an expression for laminar flow and one for smooth turbulent flow. Soulsby suggests a transition between these at a Reynolds’ number of 5·10^5. However, the transition is taken at a Reynolds’ number of 1·10^5, because this is where the two expressions cross. There are many other expressions for the wave friction factor, for different conditions. Factors to account for the effect of excessive turbulence levels, such as given by CUR/RWS and van Kessel and Stam, are ignored. These would require detailed turbulence information and would make the scour protection design unnecessarily site specific. Soulsby gives an implicit expression for the wave friction factor that is valid in
smooth, transitional and rough turbulent flows and which has a large range of applicability, including typical bed grain sizes. This expression has been tried, but the solution becomes very small for small waves, with low Reynolds’ numbers. With further reduction of wave height the implementation did not find a solution, which would be a thread to the stability of the tool. The implemented model for shear stress due to waves has been verified by comparison of results for various cases with the results of other models.

4.7.10 Array efficiency

To determine the array efficiency, the power of each of the turbines needs to be assessed as a function of wind speed and wind direction. The power of the turbine is determined from the power curve, which is entered by the user, and the local wind speed at the turbine. The assessment of wake effects on the local wind speed is only performed for wind directions between 0° and 90°. For angles between 180° and 270° the powers can be determined from the point symmetry of the inflow and farm geometry. For the two other quadrants the losses can be determined from the mirror symmetry.

The wind speed deficit in the wake of a single turbine is represented by the Jensen model. However, the later formulation of Katić et al. is used, because it expresses the wake effect as a function of the thrust coefficient rather than of the induction factor. Jensen’s model gives an explicit expression for wind speed in the wake as well as an explicit expression for the wake geometry. There are various alternative models, such as the ones of Ainslie and Larsen. These have not been chosen, because these are computationally much more demanding. Their implicit expressions of the wind speed take much more time to solve. Furthermore, the wake geometry of Jensen’s model leads to an efficient algorithm to determine the incidence of wakes in a wind farm, as will be discussed later. The wake is assumed to expand freely, without consideration of the effect of the sea surface on its development.

The wind speed deficit in a region where two or more wakes are mixed is taken to be the root of the summed squares of the wind speed deficit of the individual wakes. The wind speed deficit of the individual wakes is determined as if these wakes propagated independently. This approach is applied both to the situation where wakes develop independently behind the turbines and mix at a downstream position and to the situation of the mixed wake behind a turbine that operates in the wake of an upstream turbine. The approach of Katić et al. for two wakes is taken and expanded to multiple wakes according to Grady et al. and Mosetti et al. This means that the applied approach also copies the implicit assumption that all wind speed deficits are determined with respect to the undisturbed wind speed, even for wind turbines that operate in the wake of an upstream turbine. Frandsen and Jensen suggest other models for the wake effects of a line of turbines. These are not used, because these are only valid for wind directions aligned with the line of turbines and no guidelines are provided on how to apply these models in more complex mixed wake geometries.

When one or more wakes partially overlap with the rotor area, the local wind speed at the rotor is assumed to be the wind speed averaged over the rotor area, with each wake and the undisturbed wind speed contributing proportional to the area that each velocity covers. Wind speeds in mixed wakes are determined before they are used in the
averaging process. The geometry of incident wakes is shown in Figure 4-13 for two wakes that have a mixing area in the rotor plane. The incident wakes divide the rotor area in parts and for each part the area can be determined and the turbines can be identified for which the wake effects have to be considered. Analysis of several wind directions and turbine spacings revealed that wake-wake intersection points rarely appear inside the rotor area. Therefore, the applied algorithm ignores that mixed wake incidence can be fully enveloped by the rotor area. The effect is that the more-or-less triangular areas shown just above and below the mixed wake area can get inappropriately assigned to wakes, in the rare cases that they occur. The area of the wake incidence is calculated according to the method of Weisstein.304

Because the wake geometry in Jensen’s model is independent of the wind speed and operating conditions of the wind turbines, the incidence of wakes is determined only once for each turbine spacing. In this process, the size of each part of wake incidence on the rotor plane is stored, along with the indices of the turbines with wakes on that part. The wake incidence is determined for only one rotor, being the one in the downwind corner of the farm. The wake incidence on the other turbines can be determined from translation symmetry, as illustrated in Figure 4-14. The algorithm only needs to re-index the identification of turbines from which the wakes originate and ignore indices that are outside the valid range for turbines inside the farm boundaries. It has been assessed whether the wakes of far upstream turbines can be ignored, to reduce the evaluation time. However, for many wind speeds and wind directions this doesn’t seem to have much merits. For instance, a typical value for the thrust coefficient in the partial load region is 0.8. In that situation it takes a distance of 30 times the rotor diameter for the wind speed to recovered to 95% of its undisturbed value and 80 times to reach 99%.

The wake incidence is a function of the wind direction and is determined for 2.5° steps. To expedite the wake incidence analysis, for each of the turbines the wind directions are stored where partial and full wake incidences on the corner turbine begin and end. After this, the wind direction just needs to be checked against these data to determine whether the turbine has a full or partial wake on the corner turbine for each wind direction step.

![Figure 4-13 Geometry of mixing wake incidence at the rotor](image)
The determination of local wind speeds starts at the turbine in the upwind corner and proceeds through the row and then to the next column, etc. For each turbine the local wind speed is determined according to the previous description. The thrust coefficient for this local wind speed is determined from data entered by the user and this thrust coefficient is stored for later use. Because this process proceeds from upwind turbines to downwind turbines, the thrust coefficients that are needed in the wake assessment are always available when needed.

This algorithm is verified for the layout and turbines of Horns Rev I. The algorithm gives an array efficiency of 90.7%. Jensen\textsuperscript{160, 161} states that the array efficiency from data at Horns Rev is 90.2%. This close correspondence is not a measure of the accuracy of the model. The measured array efficiency varied between 85.3% and 91.5% for stable and unstable atmospheric conditions and this effect is not represented in the model.

Jensen’s model and the wake mixing models are widely implemented in wind farm analysis software and have been validated. Because Jensen’s model can be calibrated with the wake expansion factor, it apparently performs at an acceptable level for array efficiency assessment. However, both models have a poor physical basis. Jensen’s model ensures conservation of mass, but with the incorrect boundary condition for the mass flow at the rotor. It doesn’t conserve momentum flow. The wake mixing is claimed to conserve kinetic energy deficit and thus to conserve kinetic energy. However, it conserves the square of the wind speed deficit, which is not a physical measure for kinetic energy and certainly not for kinetic energy flow. Besides, there are no grounds to assume that kinetic energy is conserved in the mixing process. The choice of these models for the tool should therefore be treated carefully. Currently, spacing is not restricted in the design algorithms of the tool and the choice of wake modelling will mainly affect the trade-off between wake losses and cable costs. This only indirectly affects turbine design. However, if the tool is adapted to make spacing restricted, the choice of wake model may have a more direct effect on turbine design. In the case of spacing restrictions it may be better to reduce the thrust coefficient to reduce wake losses, even though this may also give a little decrease in the power curve. This trade-off might have different results for different wake models.

4.7.11 Electrical losses and temperatures in the cables
To determine the behaviour of the electrical system, several well developed elementary models are selected from various sources\textsuperscript{12, 17, 42, 43, 208, 245, 248}. These models are combined to determine the losses and the cable temperatures for the chosen configuration of the electrical system. The following steps are taken in this evaluation:
1. Determine the infield and transmission voltage levels
2. Determine active currents in each of the cables at rated power of all turbines
3. Determine reactive currents at begin, middle and end of each cable
4. Determine temperature at begin, middle and end of each cable at rated power of all turbines
5. Determine resistive losses per unit length at begin, middle and end of each cable at rated power of all turbines
6. Determine total resistive losses in each cable at rated power of all turbines
7. Determine dielectric losses in each cable
8. Determine the no-load and full-load losses in the transformers
9. Determine the no-load losses in the shunt reactors
10. Integrate all losses over the lifetime of the wind farm

The first two steps only need to be taken when the winding ratios of the transformer change. The third step and later steps are updated each time cable dimensions are changed, because they depend on cable capacitance. Steps five through 10 are only performed for the update of the objective function. During the first three steps the effects of losses are ignored. Otherwise, an iterative procedure would be required because losses are a function of the voltage and current levels, while the voltage drops over the cables and thus the currents are a function of the losses. The models used in these steps are described below. References to voltages and currents imply the root-mean-square (RMS) values, voltages are ‘line voltages’ and currents are per line.

Step 1. The ratio of incoming and outgoing voltage of the transformers are assumed to be equal to the winding ratio and no voltage drops are assumed over cables and switches.

Step 2. Active currents are determined from the voltage and the power of all turbines in the branch of the network that is connected through the considered cable.

Step 3. Total charging currents of each cable is determined from the capacitance of the cable. The dielectric constant of the insulation material and the diameters of the conductor screen and insulation are used to assess the capacitance per unit length of the cable. Due to the configuration of the shunt reactors, the reactive current at each end of the transmission cable corresponds with half of the charging current and the reactive current equals zero at its centre. In the chosen configuration the charging currents in the infield cables are to be provided by the turbines. Therefore, the reactive current of each cable section equals the charging current at the feeding side of the cable, zero at the other end and half the charging current in the middle. Because charging currents drop linearly with distance into the cable, reactive currents vary linearly with distance. However, other intermediate values for reactive currents are not explicitly calculated. The models for capacitance and charging current are verified by comparison of results with data for standard cables from ABB.

Step 4. The temperature difference between the cable conductor and the environment is modelled according to Moore. This model determines the temperature difference at which the heat flow through the thermal resistance of several layers of the cable and through the surrounding soil equals the heat generation from the resistive losses in the
conductor and the dielectric losses in the insulation. The thermal resistances follow from the thermal resistivity of the cable materials and the soil, as well as the geometry of the cable. The thermal resistance between the conductor and the sheath is determined according to IEC 60287, 1994, as described by Anders\textsuperscript{11}. This method requires a geometric factor and screening factor, which are specified in graphs. Curve fits have been made to express the factors mathematically. To avoid unrealistic extrapolation of the graphs, the thermal resistivity is not allowed to become lower than that of a single core cable, for which an analytic expression exists. The resistive losses are determined from the active and reactive currents, assuming Ohmic resistivity at the maximum allowed operational temperature. This assumption avoids iteration because these losses are a function of temperature and temperature is a function of the losses. To determine the dielectric losses the tangent of the phase angle between cable charging current and capacitive charging current is assumed to be 0.0004. To verify the model the maximum current at which the allowable temperature is reached is determined for several cable dimensions in predefined conditions for the burial depth of the cable, the temperature of the surrounding soil and seabed thermal resistivity. The results are compared to the current rating of standard cables from ABB\textsuperscript{5} for these conditions.

Step 5. In this step the resistive losses per unit length are again determined from the active and reactive currents, but now the actual temperature determined in the previous step is used to determine the Ohmic resistivity. A sheath loss factor and armour loss factor are included in the model. The resistive losses for active currents and reactive currents are determined separately, because the latter depends on the transported power, while the former doesn’t.

Step 6. A second order polynomial is fitted to the losses per unit length at the ends and middle of the cable, using a Lagrange form interpolating polynomial\textsuperscript{207}. This polynomial is integrated to get the total loss in the cable. Both the fit and the integration use explicit analytical expressions. Under the implicit assumption that the effect of temperature on resistivity is negligible, this process gives an exact solution. The resistive losses are proportional to the square of the total currents, which is the sum of the squares of active and reactive currents. Because the reactive currents vary linearly over the cable, the resistive losses per unit length vary with the square of the distance along the cable. Therefore, they are fitted exactly with a second order polynomial.

Step 7. Dielectric losses are determined in a straightforward way, again assuming the tangent of the angle between cable charging current and capacitive charging current to be 0.0004.

Step 8. The no-load loss and the full load loss of the transformers are determined from curve fits to data of actual transformers. The data are taken from Günther\textsuperscript{128}. This data set covers only one smaller transformer, of 3.5 MW. Because only this transformer is the only representative for transformers in the turbine, the curve fits are forced through the data of this transformer. When this is not done, the losses of the curve fit at 3.5 MW become about twice as high as those in the data.

Step 9. The losses in the reactive power compensation are set at 0.15% of the power of the shunts, following the suggestion of Brakelmann\textsuperscript{43}. This loss is independent of the power being transported through the system.
Step 10. The no-load losses of the transformers, the dielectric losses of the cables, the resistive losses due to reactive currents in the cables and the losses of the shunt reactors are summed and multiplied with the lifetime of the wind farm. These losses are independent of the power that is transported through the electrical system. The other losses are determined per wind speed bin and multiplied with the number of hours of occurrence of the bin. To determine the other losses, the full load losses of the transformers and the resistive losses due to active currents in the cables are summed. For each wind speed, this loss is multiplied with the square of the relative power. The relative power is the sum of the power of all wind turbines at the wind speed, divided by the rated power of the farm. This approach follows the model of Schoenmakers\textsuperscript{248} and is based on the observation that these losses are proportional to the square of the active currents and the active currents are proportional to the transported power. At lower wind speeds the temperature in the cable will be less and thus the resistive losses will be further reduced. This effect is ignored in the model, to avoid calculation of cable temperatures at several wind speeds. This model also ignores that wake effects would also lower the transported power at lower wind speeds. Furthermore, losses in switchgear and other components of the electrical system are neglected.

4.7.12 Maintenance logistics

Maintenance logistics has been modelled by others in various ways to estimate turbine availability and maintenance costs. For instance, downtime of turbines after failure has been modelled with average waiting times for reordering of spare parts, waiting for good weather, travel time and repair time\textsuperscript{238}. However, such models are not sensitive to parameters such as shift length and number of crews, since they do not include the effect of a waiting list for repairs. Downtime has also been determined from comprehensive simulation\textsuperscript{143}. This is computationally intensive and the response of the objective function to variation of for instance reliability and distance to the harbour may not be smooth. The latter effect even occurs when the simulation doesn’t use random parameters. Therefore, an analytical statistical model is developed that has a more gradual response and that includes the effect of shift duration, number of crews, number of shifts etc. Because several of the inputs for this model only take discrete values, such as the number of crews, the model still exhibits discontinuities in the response, making it unsuitable for gradient based optimisation. As can be read in Section 4.5.4, the character of the response is nevertheless predictable and the model is suitable for other optimisation algorithms.

The most important parameters to come out of the logistics analysis are the total number of failures and preventive maintenance visits, as well as the downtime associated with them. The latter is used to determine the average availability for the energy yield estimate, while the former is used to assess costs of consumables, vessel rent and lifting equipment. Figure 4-15 shows the failures and repairs of turbines over time and how this is affected by a period in which the turbines cannot be accessed. The figure also defines the terms for different phases in logistics, being storm, catch up and steady state. In the catch up period turbines are repaired that failed during the storm. Once this is finished, turbines are repaired that failed during this repair period. This is repeated until the only broken down turbines are the ones that already failed before the storm.
The downtime is formulated per phase, per storm cycle, per failure, per failure type and per turbine and then summed up. As an example, consider the downtime, $t_{down,i,j,s,k}$, due to the failure at time $t_{fail,i,j,k}$ and repair at time $t_{repair,i,j,k}$ indicated by the dashed double arrow line in Figure 4-15. This appears in the summation as:

$$
t_{down,i,j,s,k} = \left( t_{e,st,i,j,k} - t_{fail,i,j,k} \right) \mathbb{1}_{t_{fail,i,j,k} < t_{e,st,i,j,k}} + \left( t_{repair,i,j,k} - t_{b,cu,i,j,k} \right) \mathbb{1}_{t_{repair,i,j,k} < t_{b,cu,i,j,k}} \tag{4-20}
$$

in which:

- $i, j, s, k = \text{indices for the identification of respectively: turbine, failure type, individual storm cycle and individual failure}$
- $st, cu = \text{indices for the identification of storm period or catch-up repair period}$
- $b, e = \text{indication of beginning and end of that period}$

The downtime of the example is separated into two terms, because it occurs in two periods. The terms in the summations of the downtimes and failures are broken down into more detailed parts and are ordered to get groups of terms that can be conveniently modelled. Mostly, the groups represent one of the three periods in a storm cycle: storm, catch up or steady state. However, for example the downtime due to waiting for lifting equipment is also a group of terms. Terms that represent the downtime due to failures that occur during a storm or during the repair period to catch up and that are not repaired in the same storm cycle are deleted. This implies that it is assumed that all failures that occur in a storm or catch up period can be repaired within the same storm cycle. If many of the failures that occur during storm or catch up cannot be repaired within one storm cycle, apparently the deployed maintenance crew cannot deal with the amount of failures.

The downtimes, as well as the number of failures are functions of stochastic parameters. Of all the fundamental parameters, only the times of failure and the durations of storm periods are treated as stochastic variables. Various other parameters, such as repair times, waiting for spare parts or equipment and sailing times, are also stochastic. However, their probability density functions are expected to be sharp peaked and therefore their assumed averages are treated as deterministic values. By assuming that
the total number of storms in a year is a deterministic value, the expected values of
downtime and failures can be modelled for one storm cycle only and multiplied with the
number of storms.

According to Rademakers et al.\textsuperscript{238}, the probability density function of the storm length
can be expressed as a Weibull distribution. The shape factor of this distribution is
shown to be typically between 0.5 and 0.6 for a wide range of accessibility limits of the
means of personnel transport. For vessel access the average storm length has been
determined as a function of the limiting significant wave height from the data provided
by Rademakers et al. for one site. A curve fit to this data gives a power law for the scale
factor as a function of significant wave height. The user can enter Weibull parameters
for storms for a reference significant wave height at the site of interest, which are
translated to the storm length distribution for vessels with different accessibility limits
using this power law.

According to van Bussel\textsuperscript{284} the failure statistics of repairable products, amongst which
wind turbines, can be modelled with a constant hazard rate. A constant hazard rate
implies a Weibull distribution with a shape factor of 1 for the probability density
function of the failure time. The mean time between failures (MTBF) entered by the
user is the scale factor of this distribution.

Many derived parameters, such as the number of failed turbines after a storm, inherit the
stochastic nature of storms and failures. This also holds true for the downtime and
number of failures for each period of the storm cycle. Analytic expressions are sought
for the expected values of these parameters. The principles that have been applied to get
these expressions are shown in Table 4-15. The number of failures during a storm,
downtime during a storm and downtime during catch up of failures after a storm are
complex compound functions of the stochastic failures and storm length. Therefore, no
analytical solution was found for their expected value with Mathematica and according
to Wolfram\textsuperscript{307} this probably means that no solution exists. However, an analytic solution
could be found for the expected values of these parameters for the average storm length.
This analytic solution has been compared with the numeric solution of the original
integral for typical values of the storm scale factor and cumulative hazard rate of all
failure types. It was found that the difference is small for the number of failures during a
storm and the downtime during a storm. For the downtime during catch up of failures
after a storm the difference is larger, because it depends roughly on the square of the
number of failures during a storm. Therefore, it would be better to implement a numeric
integration for this parameter. In the prototype the analytical approximation is used
nevertheless.
Table 4-15 Principles applied to get the analytical expressions of the logistics model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Modelling principle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storm length</td>
<td>From probability density function of storm length</td>
</tr>
<tr>
<td>Storm fraction</td>
<td>Curve fit to data(^{380}) as function of the limiting significant wave height of a vessel. Fitting function is one at a significant wave height of zero and zero with no limit on accessibility</td>
</tr>
<tr>
<td>Calm weather length</td>
<td>From storm fraction and expected storm length</td>
</tr>
<tr>
<td>Pdf of particular turbine failing in particular type at particular time during storm</td>
<td>Probability of failure conditional to being in operation at start of the storm and not having failed during the storm so far in another failure mode</td>
</tr>
<tr>
<td>Probability of number of failures after a storm</td>
<td>Integration of probability of failure of one turbine over storm duration - Binomial distribution of number of failures in farm</td>
</tr>
<tr>
<td>Mean time to repair without storm delay</td>
<td>Summation of contributions to working and delay, assuming an efficiency of crew deployment of 90%</td>
</tr>
<tr>
<td>Steady state downtime, without waiting for crew</td>
<td>From hazard rate and repair time per failure - Calculated as if there are no storms, because average availability during storm equals that of the steady state</td>
</tr>
<tr>
<td>Steady state downtime waiting for crew</td>
<td>Binomial distribution for number of simultaneously failed turbines - Number of failed turbines minus number of crews equals length of waiting list - Expected value of time that ( n ) turbines are on waiting list multiplied with the number of turbines that are on the waiting list and summed over over ( n )</td>
</tr>
<tr>
<td>Steady state total number of failures</td>
<td>Hazard rate multiplied with the up time during the steady state</td>
</tr>
<tr>
<td>Approximate value of steady state average number of operational turbines for storm failure statistics</td>
<td>From expected value of steady state downtime, neglecting downtime while waiting for lifting equipment</td>
</tr>
<tr>
<td>Number of failures during storm</td>
<td>Integration of probability of failure of one turbine over storm duration and multiplication with average number of available turbines in the steady state</td>
</tr>
<tr>
<td>Downtime during storm</td>
<td>From the probability density function of failure times during the storm and the duration till the end of the storm</td>
</tr>
<tr>
<td>Repair time during repair batch</td>
<td>From number turbines, crew deployment and mean time to repair (without storm)</td>
</tr>
<tr>
<td>Downtime during repair batch</td>
<td>Stepwise reduction of the number of failed turbines under repair after mean time to repair (without storm delay) - Continuous downtime of failed turbines of other types - Downtime of new failures as during storms</td>
</tr>
<tr>
<td>Failures during repair batch</td>
<td>As for failures during storms</td>
</tr>
<tr>
<td>Failures, repair time and downtime during all repair batches</td>
<td>Repetition of previous three steps - Stop repetition when contributions to downtime or number of failures drop below a predefined fraction of the results so far</td>
</tr>
<tr>
<td>Downtime due to preparation of failures during storm and catch-up repairs</td>
<td>Total number of failures in these periods times the preparation time, without affecting the waiting list</td>
</tr>
<tr>
<td>Downtime due to preparation of failures during steady state</td>
<td>Included in mean time to repair, but not when evaluating the waiting list</td>
</tr>
<tr>
<td>Parameter</td>
<td>Modelling principle</td>
</tr>
<tr>
<td>--------------------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Downtime due to preparation of failures that need lifting equipment</td>
<td>Only included when preparation time is longer than the minimum time needed for the lifting equipment to arrive</td>
</tr>
<tr>
<td>Number of mobilisation times for lifting equipment</td>
<td>Binomial distribution of the number of failures as a function of time - Estimation of the probability that the lifting equipment is mobilised for n failures - Number of times that lifting equipment is mobilised for n repairs from total number of failures over the lifetime</td>
</tr>
<tr>
<td>Downtime while waiting for lifting equipment</td>
<td>Based on assumption that the first failed turbine has to wait the full mobilisation time and the next turbines have to wait half the mobilisation time plus half the time needed to repair previously failed turbines (for the same mobilisation) - Summation over number of repairs per mobilisation from 1 to ( \min(\text{number of turbines in farm, 100}) )</td>
</tr>
</tbody>
</table>

While solving the logistics model, the following checks are performed:

- Does the number of failures increase during the catch up period, indicating that crew deployment is insufficient to handle the failures after a storm?
- Does the duration of the catch up period exceed the average calm weather period, meaning that over the lifetime there is not enough calm weather to catch up repairs after the storms?
- Is crew deployment sufficient to perform all preventive maintenance?

There are many pitfalls in modelling on the basis of statistical properties. Therefore, many verifications are done along the way. Examples are:

- The probability density function of failure during storm is expected to start at the hazard rate and decrease to zero, which is indeed the case
- The expected downtime during one storm gets close to the storm length for very small MTBF and close to the expected value for a constant hazard rate for large MTBF, as expected
- For a short storm the expected number of failures after the storm determined from the probability density function of the number of failures is close to the value obtained from a constant hazard rate
- The expected value of the number of failures during a storm is also expressed in an integral of the binomial distribution of the number of failures after a storm and this gives the same numerical results as the used expression
- The expected values over all storms of number of failures during storms, downtime during storms and downtime during catch up of failures after a storm from numeric integration with the probability density function of storm length gives results similar to the expected value for the average storm length, if the probability density function is sharp peaked
- The total number of failures from the model is less than the number of failures calculated from a constant hazard rate
- The total downtime from the model is higher than the downtime calculated with a constant hazard rate and the mean time to repair and if the storm fraction goes to zero and the number of crew per shift goes up, the differences become smaller
“Unlike results from the theory-testing tradition, the form of design research I have described here does not lead to results with statistically determined confidence levels.”

Edelson, 2002

5 Appraisal of the wind farm design emulation tool

5.1 Purpose and methods of appraisal

The purpose of the work that is described in this chapter is to provide confidence in the emulation of offshore wind farm design that is performed by the tool. The word ‘appraisal’ is used for this activity, to distinguish it from ‘validation’ of the utility of emulation that is presented in the next chapter, as is explained in Section 2.2.2. This appraisal focuses on the performance of the design emulation algorithms with the selected models. The verification of the implementation of the physical models is presented in the previous chapter.

The appraisal of the design algorithms is more than a check that no errors have been made when coding them. It addresses the quality of the design result of the tool, when compared with that of realised wind farms. However, the tool cannot be expected to yield the same results as realised designs. First, the wind farm configuration that is implemented in the tool may differ from those of the compared wind farms. Second, even when the configurations correspond, there may be different design solutions that perform almost equally well. This is the principle of Pareto optimality, where multiple designs can overall have the same value but score differently on different criteria. Since there is no unique good design solution, the tool can only be appraised for its usefulness. This lack of a ‘truth’, against which the tool’s performance can be measured, is the origin of the quote of Edelson at the beginning of this chapter. As a consequence, differences that appear in the comparison should be interpreted carefully. They can either signal acceptable differences between emulated and realised designs or indicate inappropriate modelling.

When valuating the usefulness of the tool, its purpose should be kept in mind. The tool is intended to help wind turbine designers assess trade-offs that originate in design changes of the rotor-nacelle assembly. More precisely, the tool is a prototype of such software, to be used in the framework of this research and with potentially a short lifetime. Therefore, there is emphasis on the following aspects:
1. reasonableness of the design results
2. appropriate response of design solutions to changes in the inputs
3. acceptable speed and stability for application of the tool by a test panel

The first aspect is covered in Section 5.2. That section compares the emulated solutions for three wind farms, with their realised counterpart. The site data, number of wind turbines and data of the rotor-nacelle assemblies have been collected from publications to generate the input data for the emulations. The results of the emulations are compared with descriptions of the realised wind farms. Differences are discussed and further analysed when necessary. The first wind farm that is selected for this activity is Horns Rev 1. There is much information available for this wind farm and its configuration matches fairly well with the one implemented in the tool. Being developed more than 10 years ago its design doesn’t include the lessons learnt that current developments may apply. However, such lessons are arguably also not represented by the engineering and cost models in the tool. Furthermore, the choice for a less recent wind farm stimulates a focus on the quality of the tool, rather than on a discussion of the quality of realised recent wind farm designs. The other two wind farms that are selected are Barrow Offshore Wind (BOW) and Offshore Wind farm Egmond aan Zee (OWEZ). There is also a fair amount of information available for these wind farms. They are dissimilar from Horns Rev 1, but mutually they have several similarities. This will demonstrate the ability of the tool to design for different situations, as well as to show nuances.

The second aspect is covered in Section 5.3. That section shows several effects in the wind farm designs that result from changes in rotor-nacelle assembly, farm size and site conditions. The wind farm Horns Rev 1 is chosen as a reference, for the same reasons as mentioned earlier. Additional cases are studied to interpret some of the results. Small variations in input data for Horns Rev 1 are used to evaluate the smoothness of the design response, because erratic behaviour of the response complicates the use of the tool to optimise the rotor-nacelle assembly.

The third aspect is treated in Section 5.4. Several emulations are performed to get an indication of emulation speed and dominant aspects that influence this speed. Low emulation times are desirable, to achieve the low burden on the people that evaluate the tool. The stability of the emulation, particularly associated with the optimisation and root finding algorithms, is tested by using a wide range of inputs.

The suitability of the tool to test the validity of the design method is discussed in Section 5.5, which draws the conclusions of this chapter.

5.2 Emulation of the design of three existing wind farms

5.2.1 Inputs and results

The designs of the wind farms Horns Rev 1, BOW and OWEZ have been emulated with the tool. The inputs of the emulations consist of turbine properties, site conditions and the sizes of the wind farms. Horns Rev 1 makes use of V80 turbines of Vestas, while both BOW and OWEZ utilise Vestas’ V90. All data for the inputs as well as data about the realised wind farm designs are collected from public information. This enables an open discussion of the emulation results. A disadvantage of this approach is that not all
needed data is available. For some inputs assumptions have been made or data that was not directly available was obtained by deriving it from related data. Complete lists of inputs that were used for the emulation are given in Appendix E, with references to sources and descriptions of assumptions and derivations. The Horns Rev site and the V80 are best represented by the input data, as more information was found for this farm than for the other two. Therefore, correspondence between the emulation and the realised wind farm for Horns Rev is expected to be most representative of the performance of the tool.

Results of the emulations and data of the realised wind farms are discussed in the next sub sections per discipline and for the system level parameters. Each sub section starts with a table of the relevant data. The tables only show parameters that characterise the wind farm or for which comparison data has been found for at least one of the realised wind farms. The tables only provide the data values, to keep them compact. Appendix F gives references to sources for data of the realised wind farms and several remarks about the interpretation of the data from these sources.

### 5.2.2 Support structures

Table 5-1 gives the emulation results and data of the realised wind farms pertinent to the support structure design. For all sites the water depth at the deepest location has been used in the emulation. Therefore, when there is a range of values for the realised support structure designs, the largest values are considered to be the appropriate ones for the comparison.

Hub heights of the emulated designs are consistently lower than those of the realised support structures. The emulated hub heights are identified to be at the lowest constrained value. Informal discussion of this aspect with various people confirms that this is indeed generally found to be the optimal result. The use of standardised (onshore) towers, omission to fully optimise hub height and differences in the applied constraints are potential reasons for the higher values in the realised wind farms, but these hypotheses have not been validated. The differences for the two more recent farms are smaller than for the older farm and are no reason for concern about the performance of the tool.

Diameters and wall thicknesses of support structure elements as well as pile penetration depth are also almost consistently lower in the emulation than in the realised wind farms. By exception, for OWEZ the emulated transition piece diameter and tower base diameter exceed the realised ones. This is the consequence of a difference in the configuration. The emulated design corresponds to a transition piece that fits over the pile, while the actual transition piece at OWEZ goes into the pile. This also relates to the larger realised pile diameter at OWEZ. This large diameter is a consequence of stiffness requirements, which is not represented in the design algorithm of the emulation. The large difference in penetration depth for BOW is also caused by a difference in configuration. Unlike the emulated design, BOW doesn’t apply scour protection and allows a scour hole to arise. This leads to a region of the pile that is not supported by soil, increase in the moments in the foundation and a reduction in overburden pressure in the soil. Consequently, a stronger and longer pile is needed in the realised wind farm.
The lower hub heights are at least one cause of the lower diameters and wall thicknesses, because these lead to lower bending moments in the structure. To appraise the magnitude of this effect, the emulations have been repeated with the hub heights constrained at the realised hub heights. The results are shown in Table 5-2. The correspondence improves, particularly for Horns Rev. One of the remaining causes of the differences could be inappropriately low representation of the loads in the emulation. This may be partly due to the simplifications in load calculations and the reduction of the number of load cases. However, it may also be caused by errors in the input data. Much of the RNA data that is used for the load calculations is not obtained directly from a reliable source. Since the values for the piles of BOW and OWEZ differ much more than those for Horns Rev, it is likely that the inputs for the V90 are less

<table>
<thead>
<tr>
<th></th>
<th>Horns Rev</th>
<th>BOW</th>
<th>OWEZ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>70</td>
<td>60.8</td>
<td>75</td>
</tr>
<tr>
<td>Platform height (MSL+)</td>
<td>9</td>
<td>10.3</td>
<td>15</td>
</tr>
<tr>
<td>[m]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tower base diameter [m]</td>
<td>4</td>
<td></td>
<td>4.6</td>
</tr>
<tr>
<td>Transition piece</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diameter [m]</td>
<td>4.3</td>
<td>4</td>
<td>~5</td>
</tr>
<tr>
<td>Length [m]</td>
<td>14-18</td>
<td>17.8</td>
<td>~22</td>
</tr>
<tr>
<td>Overlap$^a$ [m]</td>
<td>6</td>
<td>5.4</td>
<td>~7</td>
</tr>
<tr>
<td>Pile</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diameter [m]</td>
<td>4</td>
<td>3.72</td>
<td>4.75</td>
</tr>
<tr>
<td>Thickness [mm]</td>
<td>50</td>
<td>44</td>
<td>49</td>
</tr>
<tr>
<td>Length [m]</td>
<td>30-33</td>
<td>35.2</td>
<td>54-62</td>
</tr>
<tr>
<td>Penetration [m]</td>
<td>22-24</td>
<td>23.9</td>
<td>29-39</td>
</tr>
<tr>
<td>Masses [$10^3$ kg]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tower</td>
<td>160</td>
<td>84</td>
<td>153</td>
</tr>
<tr>
<td>Transition piece</td>
<td>80-100</td>
<td>69</td>
<td>115</td>
</tr>
<tr>
<td>Pile</td>
<td>125-155</td>
<td>139</td>
<td>400-450</td>
</tr>
<tr>
<td>Scour protection</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diameter [m]</td>
<td>27</td>
<td>22.3</td>
<td>25.6</td>
</tr>
<tr>
<td>Thickness [m]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scour protection – Armour layer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grain size [mm]</td>
<td>350-550</td>
<td>210-320</td>
<td>180-280</td>
</tr>
<tr>
<td>Thickness [m]</td>
<td>0.8</td>
<td>0.45</td>
<td>0.39</td>
</tr>
<tr>
<td>Thickness near pile [m]</td>
<td>0.8</td>
<td>0.67</td>
<td>0.57</td>
</tr>
<tr>
<td>Scour protection – Filter layer 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grain size [mm]</td>
<td>30-200</td>
<td>19-48</td>
<td>16-40</td>
</tr>
<tr>
<td>Thickness [m]</td>
<td>0.5</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Scour protection – Filter layer 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grain size [mm]</td>
<td>2-3</td>
<td>1-4</td>
<td>2-5</td>
</tr>
<tr>
<td>Thickness [m]</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
</tbody>
</table>

$^a$ This is not a fair appraisal, since data from Horns Rev, BOW and OWEZ were used to calibrate the design algorithm for this parameter.
representative than those for the V80. Similarly, differences in the pile penetration depth may be due to the simplified foundation and design models as well as due to misrepresentation of the soil properties. Information about soil conditions were not found for OWEZ and the clay layers at BOW exhibit behaviour that cannot be represented by the used model for cohesionless soils. The lack of data for OWEZ may be an acceptable explanation for the larger part of the difference in pile penetration depth at that site. The larger difference for BOW has been explained above. When the soil data and configuration are reasonably well represented in the model, the difference of 1 m in pile penetration depth at Horns Rev is considered to be an indication of the correspondence between emulation and reality.

The differences in diameters, wall thicknesses and pile penetration depths are also reflected in the differences in the masses. In addition, the lengths of the various elements of the support structure have an effect on the masses. By themselves, the differences in length are not a concern, as these mainly reflect small differences in the selected heights for the transitions between the elements. Considering the close match between platform heights for all farms, the tower lengths in the constrained emulation of Table 5-2 will be close to the realised ones. Yet, the tower masses for Horns Rev and BOW in Table 5-2 are considerably lower than the realised ones. This is partly due to the omission of secondary steel mass in the model, which is probably included in the values given for the realised farms. However, this is insufficient explanation for the large remaining difference, which is a point of concern. Since the tower base dimension and tower length are close to the realised values, the remaining difference will be associated with differences in the wall thicknesses. For the constrained condition of Table 5-2, the wall thicknesses reduce from 26 mm at the base to 9 mm at the top. Although no reference information could be found for this particular tower, the thickness at the base is considered reasonable, while the thickness at the top is exceptionally low. The low values near the tower top are due to the low bending moments caused by the thrust on the rotor. As a working hypothesis for future improvements of the tower design emulation it is proposed that the lack of accurate modelling of fatigue causes the difference in this region. The large effect of fatigue on the design of this region of the tower is confirmed by Verma.396

For the transition pieces of Horns Rev and BOW the omission of secondary steel mass in the model and the differences in lengths are expected to explain most of the differences in mass. The differences in the masses of the monopile follow directly from

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**Table 5-2 Emulation results with hub heights constrained at the realised hub heights**

<table>
<thead>
<tr>
<th></th>
<th>Horns Rev</th>
<th></th>
<th>BOW</th>
<th></th>
<th>OWEZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pile Diameter [m]</td>
<td>4</td>
<td>3.97</td>
<td>4.75</td>
<td>4.41</td>
<td>4.5-4.6</td>
</tr>
<tr>
<td>Thickness [mm]</td>
<td>50</td>
<td>46</td>
<td>50</td>
<td>40-60</td>
<td>48</td>
</tr>
<tr>
<td>Penetration [m]</td>
<td>22-24</td>
<td>25</td>
<td>29-39</td>
<td>29.7</td>
<td>30</td>
</tr>
<tr>
<td>Transition piece diameter [m]</td>
<td>4.3</td>
<td>4.27</td>
<td>~5</td>
<td>4.71</td>
<td>4.3</td>
</tr>
</tbody>
</table>

**Masses [10^3 kg]**

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tower</td>
<td>160</td>
<td>113</td>
<td>153</td>
<td>114</td>
<td>94</td>
</tr>
<tr>
<td>Transition piece</td>
<td>80-100</td>
<td>76</td>
<td>115</td>
<td>149</td>
<td>147-160</td>
</tr>
<tr>
<td>Pile</td>
<td>125-155</td>
<td>164</td>
<td>400-450</td>
<td>228</td>
<td>230-270</td>
</tr>
</tbody>
</table>
the differences in the diameter, wall thickness and length, that have been discussed above.

Considering the previous explanations of the larger absolute differences found between the emulated and realised dimensions and masses of the support structure, the variations in the emulated values follow the variations in the realised wind farms fairly well. This is of larger importance for the use of the tool than the absolute values. This indicates that the results properly represent the effect of changes in the site conditions and RNA properties on the support structure design.

A detailed comparison of the scour protection design can only be made for Horns Rev. BOW doesn’t have scour protection in reality and for OWEZ only the diameter and thickness of the protection could be found. The correspondence of the values for the latter two parameters for OWEZ is fairly well.

The rock size of the armour layer of the emulated design is larger than the realised protection. A sensitivity study showed that this rock size is very sensitive to the model and input data for the hydrological conditions. The emulated scour protection design for Horns Rev yielded two filter layers and one armour layer. The realised design only has one filter layer. Since the realised filter layer is a gravel mattress, rather than riprap, it probably has a better retaining capacity of the fine seabed sand. Furthermore, the filter layers of the emulated design need to bridge a larger gap between the seabed grain size and the larger armour rock size. An independent design of scour protection for the conditions at Horns Rev made by Halfschepel also resulted in two filter layers and armour rock with a $d_{50}$ of 0.45 m, which is close to the emulated values. Differences in scour protection design are not further analysed, since the sensitivity of the scour protection design to variation in RNA data is expected to be small. The design algorithm and physical models reveal that RNA properties only influence scour protection design through their effect on monopile diameter. The scour protection design is sensitive to site conditions, but with a contribution of less than 1.6% to the LPC for Horns Rev it is not expected to play a noticeable role in the optimisation of RNA parameters.

### 5.2.3 Electrical system

Table 5-3 gives the emulation results and data of the realised wind farms pertinent to the design of the electrical system.

The burial depths of the transmission cables and infield cables correspond well and confirm that the KBE rule for this design variable is appropriate.

Both Horns Rev and Barrow only have reactive power compensation onshore, whereas the emulated design configuration divides this over an onshore and an offshore shunt reactor. For the comparison of the results, the sum of the powers of these reactors can be compared with the realised compensation. These compare very well. For OWEZ no data has been found about reactive power compensation.

The transmission voltages for Horns Rev and BOW are of similar magnitude in the emulated designs and in reality. The difference for OWEZ is extremely large, because
there is no offshore transformer station in the realised wind farm. This wind farm transmits the energy through three cables at the infield voltage level. The transmission voltage at Horns Rev is higher in the emulation than in reality. This is caused by a difference in the configuration. For the realised wind farm it was chosen to connect the transmission cable directly to the grid, without transformer. This saves the costs of an onshore transformer. However, the emulation operates under the condition that costs are incurred for an onshore transformer anyway. Apparently, this leads to a higher optimal voltage, in which case the active currents are lower. The same applies to the differences in transmission voltage for BOW, which also doesn’t have an onshore transformer. It is consistent with expectations that the emulated voltage level at Horns Rev is higher than at the other two farms. This wind farm is farther away from the grid connection point and the transmission system has to transmit a higher power. The emulated voltages for BOW and OWEZ are of similar magnitude. The power of BOW is slightly lower than at OWEZ, but it has to be transmitted over a larger distance. Although this qualitatively justifies the results, no further attempt has been made to justify whether the absolute values of the optimum voltage levels are reasonable.

Before discussing the infield electrical system, the infield topologies of the realised wind farms are explained. For the realised wind farm at Horns Rev three different cable sizes are used for power collection. Horns Rev uses an infield topology that differs from the emulated configuration, as shown in Figure 5-1. The biggest cable connects two rows to the transformer and therefore carries much more power than the corresponding connection per row in the emulated configuration. The smallest cable is used to connect turbines near the end of the row, because these only transport energy of a few turbines. The intermediate cable is used to connect turbines at the beginning of the rows and to connect two rows. The fairest comparison is made with this cable, with 150 mm$^2$ cross-section of the conductors. For BOW, the topology of the cables is the same as in the emulation, but two different cable sizes are used. The smaller cables are used near the end of the row, while the bigger cables are used at the beginning of the row and to connect a row to the transformer. The fairest comparison with the cables designed in the emulation is made with these bigger cables, with 300 mm$^2$ cross-section of the conductors. The cable topology for OWEZ differs much more from that of the emulation. It is shown in Figure 5-1. Again, the smaller cables are used at the end of the

| Table 5-3 Results of emulated and realised electrical system designs of three wind farms |
|----------------------------------|-----------------|-----------------|-----------------|-----------------|
|                                  | Horns Rev       | BOW             | OWEZ            |                 |
| Transmission                     |       |       |       |       |       |       |                 |
| Burial depth [m]                 | 1-3   | 3     | 3     | 3     | 1.5-3 | 3     |                 |
| Conductor area [mm$^2$]          | 630   | 346   | 300   | 228   | 500   | 251   |                 |
| Voltage level [kV]               | 122-169| 189.2 | 132   | 151.5 | 34    | 149.5 |                 |
| Offshore reactive power compensation [MVAr] | 80    | 38    | 24    | 13    | 6.6   | 6.6   |                 |
| Onshore reactive power compensation [MVAr] |       |       |       |       |       |       |                 |
| Infield                          |       |       |       |       |       |       |                 |
| Burial depth [m]                 | 95/150/400| 1.5 | 1.5   | 1.5   | 1.5   | 1.5   |                 |
| Conductor area [mm$^2$]          | 34    | 130   | 120/300| 145   | 120/300| 165   |                 |
| Voltage level [kV]               | 34    | 31.2  | 33    | 39.0  | 34    | 40.9  |                 |
The larger cables are used for the beginning of the row, starting at the first turbine in the string. Therefore, these cables carry the power of 11 turbines, at most, whereas the infield cable in the model only carries the power of 9 turbines. Nevertheless, for the infield cable the fairest comparison is made with the cable with 300 mm$^2$ cross-section of the conductors.

Like the transmission voltage, the infield voltage levels are of similar magnitude in the emulated designs and in reality. Nevertheless, there are clear differences. Again, the mutual differences for the emulations of the three farm designs are consistent with expectations. The total cable length for each string of turbines in a row is of similar magnitude. In the emulation, the maximum power in a string of the Horns Rev wind farm is 16 MW, while it is 24 and 27 MW for BOW and OWEZ, respectively. The maximum power in a string of the realised OWEZ farm is actually larger, as explained above. Consequently, the infield voltage level for the emulated OWEZ farm is slightly larger than that for BOW and both are much larger than that for Horns Rev. The choice of voltage levels around 34 kV for all three realised wind farms may be related to the lower costs of standardised components, but this is not further investigated.

A direct comparison of cable cross-sectional area of the conductors reveals large differences, both for the transmission cable and for the infield cable. However, the design of the cable cross-sectional area is influenced by the voltage level at which the cable is operated. The higher the voltage level, the smaller the optimal cross-sectional area of the conductor will be, in general. This effect is indeed consistent with the differences in voltage level and cable cross-sectional area for both infield and transmission cables. To further appraise that the cable cross-sectional area is designed correctly, two tests are performed. First, the wind farms are redesigned with the tool under the constraint that the voltage levels correspond with those of the realised farms. This allows a direct comparison of the cross-sectional areas, without the previously mentioned influence of voltage level. Second, the operational conditions and designs of the infield and transmission cable of Horns Rev are compared with current carrying capacities of cables from ABB.

Table 5-4 shows the results of the constrained emulations. For Horns Rev the constrained emulation has been done twice. The actual public grid at the connection point, and therefore the transmission, can operate within a range of voltage levels. The
emulation has been done for the minimum voltage level and for a normal operational voltage level. Also for OWEZ two emulations have been performed. In both emulations the infield and transmission voltages are set to 34 kV. In the first emulation this is the only difference with the earlier emulation. This emulation gives a fair comparison for the infield cable cross-section, albeit that it is designed for 9, rather than 11 turbines in a row. A second emulation is done for a farm of 3x4 turbines. This gives a fair comparison for the transmission cables, each of which carrying the power of 12 turbines to shore.

The cable cross-sectional areas for the transmission cables in the constrained emulations correspond well to those realised. Small differences may be caused by the choice for standardised cables in the realised wind farms. The transmission cable in the realised wind farm at Horns Rev will need to comply with the temperature constraint when operating at the low voltage of 122 kV, but is doesn’t have to be optimised for this exceptional condition. Therefore, the realised cross-sectional area is probably slightly smaller than the emulated result. The infield cable cross-sectional areas from the emulation are still clearly smaller than those of the realised cables. As will be shown later, the spacing between the turbines in a row is larger in the emulated farm designs than in reality. The larger spacing leads to longer infield cables, which increases cable costs and electrical losses. Since cable costs have a more dominant role in the objective function than the losses, the larger spacing is expected to lead to smaller cables.

Table 5-5 shows the designs and operational conditions of the cables in the Horns Rev wind farm and the current carrying capacity of ABB cables. The table shows that infield and transmission cables are operated below the current carrying capacity, both for the emulated cable designs and the realised cables. Particularly the realised transmission cable is operated far below its capacity, because its operational voltage may drop to 122 kV. Considering the data in Table 5-5, there is no reason to be concerned about the reasonability of the cable design.

### 5.2.4 Operation and maintenance

Table 5-6 gives the emulation results and data of the realised wind farms pertinent to the design of the deployment of crew and equipment for maintenance. No data about deployment of maintenance personnel has been found for BOW and OWEZ. Therefore,
A comparison of this aspect with the actual situation is only done for Horns Rev. Data for the number of shifts and the strategy concerning rental of lifting equipment have not been found for any of the wind farms.

The number of crews deployed in the emulation is much larger than in reality. Closer inspection revealed that the result of 5 crews is on the constraint of the minimum amount of crews needed to perform all the service and repairs. It is therefore not a larger value as a consequence of a trade-off between maintenance costs and availability. A simplified analysis of maintenance is used to appraise that the difference is not caused by an error in the models of the logistics or in the algorithm for design of maintenance deployment. The simplified analysis is based on the number of failures that is expected if there is no downtime due to logistics, caused for instance by inaccessibility during storms. The estimated number of failures, $N_{f,total,j}$, per failure type $j$, is computed from:

$$N_{f,total,j} = \frac{N_t \cdot T_{life}}{MTBF_j + T_{diagnose,j} + T_{sp,j} + T_{fix,j}}$$  \hspace{1cm} (5-1)$$

with:

- $T_{life}$ = lifetime,
- $N_t$ = number of turbines in the farm,
- $MTBF_j$ = mean time between failures of type $j$,
- $T_{diagnose,j}$ = time to perform the diagnosing activity of failures of type $j$.

### Table 5-5 Cable designs and operational conditions of cables at Horns Rev, along with current carrying capacities of ABB cables

<table>
<thead>
<tr>
<th></th>
<th>Infield Realised</th>
<th>Infield Emulated</th>
<th>Transmission Realised</th>
<th>Transmission Emulated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable cross-section [mm$^2$]</td>
<td>150</td>
<td>130</td>
<td>630</td>
<td>346</td>
</tr>
<tr>
<td>Transported power [MW]</td>
<td>16</td>
<td>16</td>
<td>160</td>
<td>160</td>
</tr>
<tr>
<td>Line voltage [kV]</td>
<td>34</td>
<td>31</td>
<td>165</td>
<td>189</td>
</tr>
<tr>
<td>Active current [A]</td>
<td>272</td>
<td>296</td>
<td>560</td>
<td>488</td>
</tr>
<tr>
<td>Reactive current$^a$ [A]</td>
<td>3.0</td>
<td>3.9</td>
<td>116</td>
<td>117</td>
</tr>
<tr>
<td>Total current (RMS) [A]</td>
<td>272</td>
<td>296</td>
<td>572</td>
<td>502</td>
</tr>
<tr>
<td>Rated current ABB cable$^b$ [A]</td>
<td>375</td>
<td>356</td>
<td>715</td>
<td>551</td>
</tr>
</tbody>
</table>

$^a$ Realised reactive current determined from interpolated charging currents from ABB data.$^5$

$^b$ Based on cable cross-section; Data of standard cables from ABB$^5$ interpolated.

### Table 5-6 Results of emulated and realised maintenance designs of three wind farms

<table>
<thead>
<tr>
<th></th>
<th>Horns Rev</th>
<th>BOW</th>
<th>OWEZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shifts per day</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Crews per shift</td>
<td>3</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Time before ordering [h]</td>
<td>901</td>
<td>0</td>
<td>69</td>
</tr>
<tr>
<td>Number of access vessels</td>
<td>1 (+1)</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Availability [%]</td>
<td>95.3-97.3</td>
<td>96.4</td>
<td>95</td>
</tr>
</tbody>
</table>

A comparison of this aspect with the actual situation is only done for Horns Rev. Data for the number of shifts and the strategy concerning rental of lifting equipment have not been found for any of the wind farms.

The number of crews deployed in the emulation is much larger than in reality. Closer inspection revealed that the result of 5 crews is on the constraint of the minimum amount of crews needed to perform all the service and repairs. It is therefore not a larger value as a consequence of a trade-off between maintenance costs and availability. A simplified analysis of maintenance is used to appraise that the difference is not caused by an error in the models of the logistics or in the algorithm for design of maintenance deployment. The simplified analysis is based on the number of failures that is expected if there is no downtime due to logistics, caused for instance by inaccessibility during storms. The estimated number of failures, $N_{f,total,j}$, per failure type $j$, is computed from:

$$N_{f,total,j} = \frac{N_t \cdot T_{life}}{MTBF_j + T_{diagnose,j} + T_{sp,j} + T_{fix,j}}$$  \hspace{1cm} (5-1)$$

with:

- $T_{life}$ = lifetime,
- $N_t$ = number of turbines in the farm,
- $MTBF_j$ = mean time between failures of type $j$,
- $T_{diagnose,j}$ = time to perform the diagnosing activity of failures of type $j$. 

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The amount of crew time that is needed is consecutively determined from the number of failures, the diagnosis and repairs times and the duration and number of service visits. The amount of time that crews can spend on repairs and service is determined from the duration of a shift, the travel time to and in the farm and an efficiency of crew deployment of 90%. For the failure data that is used in the emulation, this leads to a minimum number of crews of 4.25. Since only integer numbers of crews are considered in the emulation, this results in a deployment of 5 crews. The overcapacity implies that the crews are idle for a substantial amount of time.

The input data concerning maintenance needs originate from a study that has been performed for the owner and operator of the Horns Rev wind farm. It is therefore unlikely that the large difference is caused by a large error in the inputs. A more likely explanation is that the meaning of the number of crew in the realised wind farm differs from the meaning in the emulation. In the emulation the 5 crews perform all the maintenance, including repairs with lifting equipment and periodic service. Perhaps the 3 crews mentioned for the actual wind farm are permanently deployed for normal repairs, while additional crew is deployed for repairs with lifting equipment and service. Repairs with lifting equipment are performed day and night and need separate scheduling of crews anyway. The proposition that additional crews are deployed during service periods is supported by the fact that during these periods also an additional vessel is deployed for personnel transport.

The availability achieved in the emulation is similar to the values that have been found for the realised farm. However, the latter values are also not the actual availability. The lower value is generated with an independent model, but with the same failure data. The higher value is the original contractual availability that was promised before the wind farm was constructed. The emulated availability is higher than realised for BOW. Information about the accessibility of BOW was available, but the reliability data of the V80 has been used as the next best data for the V90. For OWEZ no fair comparison can be made. Both accessibility data and reliability data were not found for this wind farm. Availability data has only been found for the first two years of operation. It is common to have much lower, and therefore unrepresentative, availabilities during the start-up of operations.

The lack of good input data and good reference data for the realised wind farms hampers proper appraisal of the workings of this part of the emulation. The comparison of the emulation with the simplified analysis provides some confidence, but further investigation is desirable. Since failure data and operational data are notoriously hard to get, this is not further pursued within this project.

5.2.5 Layout
Table 5-7 gives the emulation results and data of the realised wind farms pertinent to the design of spacing between the turbines.
The spacings that result from the emulation are of similar magnitude as those of the realised wind farms. The two more recently realised wind farms have a clear difference in spacing for the turbines in the rows and those in the columns, with the second being much larger. This difference is not present in the realised Horns Rev farm. For the emulated results, the opposite is seen. The emulated Horns Rev design does show a larger spacing between turbines in a column, while BOW and OWEZ have a larger spacing between turbines in a row.

To further analyse this, the main effects of spacing on the objective function are identified. The spacing has a direct effect on:

- bottom lease costs (through the area used for the farm)
- array efficiency (through distances between the turbines)
- infield cable procurement, installation and decommissioning costs (through cable length)
- infield cable loss (through cable length)
- vessel rent, availability, costs of repairs (through travel time inside the farm)

The first four effects are considered to be dominant. In addition, the change in objective function due to these effects will influence the optimum of other design variables. These changes are also not considered in this analysis. To separate these four effects in the objective function, Equation (4-2) is rewritten to:

\[ \text{LPC} = \frac{C_{bl}^* + C_{infield}^* + C_{rest}^*}{\eta_{electrical}\eta_{array}E_s^*} \] (5-2)

with:

- \( C_{bl}^* \) = actualised total bottom lease costs,
- \( C_{infield}^* \) = actualised infield cable procurement, installation and decommissioning costs,
- \( C_{rest}^* \) = all other actualised costs,
- \( E_s^* \) = actualised total energy yield without electrical and array losses.

Substituting the cost models leads to the relative gradient of the LPC with respect to changes in spacing between turbines in row and column according to:

\( \frac{\partial \text{LPC}}{\partial \text{spacing}} \)
\[
\frac{\nabla (LPC)}{LPC_{ref}} = \left( \frac{\partial LPC}{\partial s_c}, \frac{\partial LPC}{\partial s_r} \right) = \frac{1}{LPC_{ref} \left( \eta_{electrical} \eta_{array} E_s \right)_{ref}} \left( 
abla_{\partial s_c, \partial s_r} \right)
\]

\[
\left( \frac{(N_c - 1)(N_r - 1)s_c dC_{bl}^{\text{infeld}}}{dA_{farm}} \right) + \frac{N_c (N_r - 1) s_r dC_{bl}^{\text{infeld}}}{dA_{farm}} \right)
\]

\[
\left( \frac{-LPC_{ref} E_s \eta_{electrical} \partial \eta_{array}}{\partial s_c} \right) + \left( \frac{-LPC_{ref} E_s \eta_{electrical} \partial \eta_{electrical}}{\partial s_r} \right)
\]

(5-3)

with:

\[
\frac{\partial l}{\partial s_c} = \begin{cases} 
\frac{N_c^2}{4}, & N_c = \text{even} \\
\frac{N_c^2 - 1}{4}, & N_c = \text{odd}
\end{cases}
\]

(5-4)

and:

\[s_c, s_r = \text{spacing between turbines in row and column, respectively,}\]
\[A_{farm} = \text{area occupied by the farm,}\]
\[l = \text{total length of infield cable,}\]
\[N_r, N_c = \text{Number of turbines in row and column, respectively.}\]

The gradient in both directions consist of a term for a change in bottom lease costs, in infield cable costs, in array efficiency and in electrical efficiency. To get a first impression of the meaning and working of Equation (5-3) the design of a wind farm with 10 rows and 10 columns has been emulated. If the row and column spacing in this wind farm are equal, the first and third term give an equal effect on LPC for changing spacing in either direction. Thus, these terms do not force the solution away from the rectangular shape. The remaining two terms represent the effect of increase in cable costs and increase in cable losses with increasing cable length. The cable length increases most with changing separation distance in the row. Since both costs and losses have a negative effect on LPC, the optimisation should move away from the square wind farm in the direction of larger spacing in the column than in the row. Indeed, for this wind farm the spacing in the column became 734 m, while spacing in the row became 693 m.

Horns Rev has a nearly equal number of turbines in rows and columns and therefore shows a similar effect in the emulation. BOW and OWEZ are long stretched wind
farms, with more turbines in the rows than in the columns. In such wind farms the gradients for cable costs and losses will become even more dominant for spacing of turbines in the row, compared to spacing of turbines in the column. As discussed above, these gradients force the solution to larger spacing in the column than in the row. However, the gradient of array efficiency is also much more dominant for changes in spacing in the row than in the column, since there are more turbines in the row. This forces the solution to larger separation within the row. Which effect dominates depends on the magnitude of the terms in Equation (5-3).

The four contributions to the gradient of the LPC in Equation (5-3) are determined for both the emulated and realised BOW wind farm, using the models of the tool. The results are shown in Figure 5-2. For the emulated wind farm the totals are close to zero. This is expected, since the gradients should reach zero when the optimum is reached. The column spacing is mainly a balance between the terms of the bottom lease costs and the array efficiency. The row spacing is a balance between bottom lease costs, cable costs and array efficiency. The cable costs are more dominant for the row spacing, since there is more cable length in the rows. The array efficiency is more dominant in the row spacing, since there are more turbines in the row, even though the row spacing is larger than the column spacing. In the realised wind farm, the cable costs are also more dominant for the row spacing than for the column spacing. This may have been a reason for the designers to make row spacing smaller than column spacing. However, the gradient of the array efficiency is much larger with respect to row spacing than with respect to column spacing. This is not surprising, since the rows have more turbines and are closer spaced. According to the model, the designers of BOW have put too much emphasis on the cable costs effect and too little on the effect of array losses. However, there may be other aspects involved that are not modelled, such as considerations of bathymetry or restrictions on the area.

Figure 5-2 Contributions to relative gradient of LPC; Left hand: change in column spacing – Right hand: change in row spacing
The values of the gradients are not analysed for OWEZ. The topology of the cables of the realised wind farm differs too much from that of the emulation. Particularly the connection of the different rows to the transformer is too different. In the realised OWEZ cable layout a larger separation between the rows comes at a cost increase that is much less than in the emulated topology, since only two low-power cables are used between the rows and the other connections go directly to shore. This explains why OWEZ can use a relatively large spacing of 1000 m between the rows.

Besides the separation between rows in OWEZ, the emulation always gets larger spacings than the realised wind farms, even though several of the realised wind farms actually don’t have to pay a bottom lease. Without bottom lease, the spacings in the emulation get even 30% to 60% larger. However, restrictions on the used area may also lead to smaller spacing. As discussed in Section 4.5.5, such project specific restrictions have not been modelled. Besides, spacing is known to not be always optimal in realised wind farms. For instance, for the Lillgrund wind farm a planned and permitted layout for 1.5 MW turbines was delayed for so long, that 2.3 MW turbines were chosen to replace the original ones at their original positions. Priority was given to maximising yield over maximising profit\textsuperscript{75}. Other studies confirm that optimum spacing may be larger than what is typically seen in realised farms, if no space restrictions are applied\textsuperscript{201}.

5.2.6 System level parameters

Table 5-8 gives the emulation results and data of the realised wind farms pertinent to system level parameters.

The electricity production is always higher in the emulation than in the realised wind farms. The difference in array efficiency due to the difference in spacing and the difference in availability contribute to this effect. In the case of Horns Rev it is also suspected that the average wind speed in the emulation is optimistically high. The effects of wind speed and availability on electricity production of the realised wind farms is very high. The variation over time is shown in Table 5-9 for Horns Rev and BOW. The low yield in early years of the projects is caused by start-up and availability, while the latter years indicate the variability of wind speed over time. Considering these variations in reality, the emulated results are sufficiently close.

<table>
<thead>
<tr>
<th>Table 5-8 Results of emulated and realised system level parameters of three wind farms; All costs are translated to 2012 values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual output [GWh]</td>
</tr>
<tr>
<td>Investment costs [M€]</td>
</tr>
<tr>
<td>LPC [€ct/kWh]</td>
</tr>
<tr>
<td>of which: Investment [%]</td>
</tr>
<tr>
<td>O&amp;M [%]</td>
</tr>
<tr>
<td>Balancing [%]</td>
</tr>
<tr>
<td>Decommissioning [%]</td>
</tr>
</tbody>
</table>
The levelised production cost of the emulated Horns Rev design is higher than the one determined for the actual wind farm. The LPC is sensitive to the assumed interest rate and economic lifetime\textsuperscript{202}. An economic lifetime of 20 years is used for the emulation, as well as for the actual wind farm, while the interest rates are very close, being 7.31% and 7.5%, respectively. The LPC of the actual wind farm is determined assuming 4200 full load hours, which corresponds to an annual energy yield of 672 GWh/y. However, the actual yield over 2004-2011 is only 612 GWh/y. This indicates that the value of the LPC of the realised wind farm is not very accurate. Much of the difference in LPC comes from the difference in contributions of operation and maintenance costs. The absolute values of the investment costs and operation and maintenance costs will be analysed later. No reference data has been found for BOW and OWEZ. The LPC of the emulations is larger than for Horns Rev by 6% and 7%, respectively. The increase in LPC is most likely associated with the reduction in farm size. Kentish Flats, Burbo Bank and Lillgrunden are three wind farms of similar size as BOW and OWEZ and have been built around the same time. Morthorst \textit{et al.}\textsuperscript{209} show that these three farms indeed have an LPC that is around 20% higher than that of Horns Rev. Considering the uncertainties in the assumptions made for the realised wind farms, the LPC values of the emulations are considered to be reasonable. However, it is noted that the LPC values are much smaller than estimates of around 16 or 17 €ct/kWh used as ballpark figures by project developers and investors\textsuperscript{206}. The difference is expected to be mainly caused by differences in economic lifetime, financing costs and taxes. It has not been investigated how much the optimum of the design variables would be affected by using project developer principles to assess LPC.

The investment costs of Horns Rev and BOW are slightly larger in the emulation than realised, while the reverse applies to OWEZ. No data has been found for further analysis of the costs of BOW and OWEZ. For Horns Rev a comparison of contributions to investment costs is provided in Figure 5-3. The figure shows that the distributions are very similar, apart from the last two. In the emulation no environmental analysis has been modelled. This analysis was very extensive and expensive for Horns Rev, due to the demonstration nature of this first large offshore wind farm. The difference for miscellaneous costs is probably due to differences in the interpretation of this category. The correspondence in investment costs is considered acceptably well, particularly considering the variability of costs. Morthorst \textit{et al.}\textsuperscript{209} show that in the period 2004-2006 the costs of onshore wind energy increased between 20 and 25%. It is not clear

\begin{table}[h]
\centering
\caption{Energy yield of Horns Rev and BOW over the years}
\begin{tabular}{lcc}
\hline
Year & Energy yield [GWh] & \\
     & Horns Rev & BOW \\
\hline
2002 & 44 & \\
2003 & 460 & \\
2004 & 367 & \\
2005 & 630 & \\
2006 & 596 & 137 \\
2007 & 660 & 198 \\
2008 & 627 & 313 \\
2009 & 581 & 270 \\
2010 & 566 & 242 \\
2011 & 670 & 321 \\
\hline
\end{tabular}
\end{table}
how these costs further developed after 2006 and how much of the developments of costs are represented in the cost models that date from various years.

No reference data has been found for operation and maintenance costs. Table 5-8 gives the contribution of O&M costs to the LPC, but this is based on assumed O&M costs of 16 €/MWh and assumed grid balancing costs of 3 €/MWh. Therefore, the confidence in the O&M costs of the emulation is provided by an analysis of the results for Horns Rev. These are shown in Figure 5-4.

The largest contributions come from costs of personnel and lifting equipment. The costs of personnel are determined in a straightforward way and are dominated by the number of crews. The number of crews in the emulation is much larger than in the realised wind farms, as is discussed in Section 5.2.4. This provides one reason for the large
contribution of O&M costs to the LPC in the emulation, which can be traced back to the input parameters and not to the models. Nevertheless, the large proportion of personnel costs indicates that future developments of the tool should address the validity and accuracy of the hourly rates for maintenance personnel. The costs of lifting equipment is determined from the number of mobilisations, the number of hours of operation and the number of mobilisations. Using the simplified O&M model that is introduced in Section 5.2.4, the costs of lifting equipment it determined to be 3.81 M€/y without mobilisations and 5.96 M€/y with one mobilisation for each failure. The emulated costs fall within this range, as expected. Therefore, also for this large contribution to O&M costs further analysis should focus on the input of failure rates and the used hourly rates of lifting equipment, rather than on the models.

The next three contributions are the costs of consumables for repairs, the grid charge and the bottom lease. The costs of consumables are almost entirely dependent on the inputs and therefore merit no further analysis of the tool. The grid charge and bottom lease are determined with very simple models. They are assumed to be a function of the annual energy yield and used area, respectively. Since their contributions to O&M costs and consequently to the LPC are significant, these models should be further analysed when absolute results of the tool are important. However, the grid charge is not expected to affect the design of the wind farm or the rotor-nacelle assembly clearly, because its effect is mainly a constant multiplication factor of the objective function. This doesn’t affect the position of its minimum. The bottom lease is shown to have an effect on the design of the wind farm, in Section 5.2.5. The assumption of having a bottom lease and the model to determine it therefore asks for further analysis, albeit not with high priority.

5.3 Responses to changes in input parameters

5.3.1 Introduction

This section discusses the response of the design emulation to changes in the input parameters. To see whether or not the emulation responds according to expectation serves two purposes. First, it gives an indication about the ability of the tool to properly determine the design of wind farms, other than the three that have been discussed above. Second, a proper response of the objective function to changes in RNA input parameters is essential when using the tool to assess trade-offs associated with variation of these parameters.

The sensitivity study is performed for the Horns Rev wind farm, using the results of the previous emulation as a reference. A selection of input parameters is made that captures different types of variations. For instance, only the drag coefficient of an idling rotor is changed to capture the effect of changes in aerodynamic loading. Parameters such as the maximum thrust and solidity of the rotor would have similar effects and have therefore not been changed. The selected parameters are changed with a representative amount. The chosen changes are expected to be unfavourable for the wind farm, so each is expected to lead to an increase in LPC. The list of parameters and the changes in their values are given in Table 5-10. Only one input parameter is changed at a time. Several parameters of the response are compared with the reference. The difference is normalised with the maximum difference for that parameter over all variations.
In the discussions of the sensitivities, the causes of changes in the response as presented in Table 5-11 will be used. The table also gives an indication of the expected magnitude of the response. Next to the direct effects of input parameters shown in Table 5-11, the effects may cascade through the evaluations and iterations. For instance, changes in design variables will consecutively affect many properties and performance parameters, which in turn may change the relative importance of parts of the LPC for the next iteration. The magnitude of these indirect changes can be assessed by following the path of the effect and using Table 5-11 for each step. However, in most cases only the direct effects will be discussed.

The next sub sections discuss the response per discipline and for the system level parameters. Each sub section follows the same structure. First, the place of appearance of input parameters in the models and design algorithm of the discipline is used to determine ‘at a glance’ whether design variables, properties and performance parameters are expected to respond. Then, a closer look at the models and algorithm is given to analyse the ‘direction of change’. Finally, it is assessed whether the ‘relative magnitudes of change’ correspond with the expectations from the right hand column of Table 5-11.

### Table 5-10 Selected input parameters for sensitivity study and their variation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Reference value</th>
<th>Changed value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Farm</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of turbines in row [-]</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>Number of turbines in column [-]</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td><strong>Site</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distance to harbour [km]</td>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td>Distance to grid [km]</td>
<td>55</td>
<td>65</td>
</tr>
<tr>
<td>Grid voltage [kV]</td>
<td>169</td>
<td>150</td>
</tr>
<tr>
<td>Grid frequency [Hz]</td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td>Wind speed scale factor [m/s]</td>
<td>10.83</td>
<td>9.83</td>
</tr>
<tr>
<td>Significant wave height [m] 1-year return period</td>
<td>3.3</td>
<td>4.0</td>
</tr>
<tr>
<td>50-year return period</td>
<td>5.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Water depth [m]</td>
<td>13.5</td>
<td>15.0</td>
</tr>
<tr>
<td>Accessibility – storm percentage [-]</td>
<td>0.6</td>
<td>0.65</td>
</tr>
<tr>
<td>Soil strength – friction angle [degrees]</td>
<td>35</td>
<td>30</td>
</tr>
<tr>
<td><strong>RNA</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Failures that need lifting – MTBF [h]</td>
<td>73000</td>
<td>63000</td>
</tr>
<tr>
<td>Failures without lifting – MTBF [h]</td>
<td>6100</td>
<td>5100</td>
</tr>
<tr>
<td>Planned service interval [h]</td>
<td>4380</td>
<td>4000</td>
</tr>
<tr>
<td>Yaw bearing diameter [m]</td>
<td>2.26</td>
<td>2.0</td>
</tr>
<tr>
<td>Rotor diameter (without changing power curve) [m]</td>
<td>80</td>
<td>90</td>
</tr>
<tr>
<td>$c_d$ of idling rotor [-]</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>$c_T$ [-]</td>
<td>[table]</td>
<td>1.1 times</td>
</tr>
<tr>
<td>Power [W]</td>
<td>[table]</td>
<td>0.9 times</td>
</tr>
<tr>
<td>Generator voltage [V]</td>
<td>690</td>
<td>600</td>
</tr>
<tr>
<td>RNA purchase price [M€]</td>
<td>1.5</td>
<td>2.0</td>
</tr>
</tbody>
</table>

In the discussions of the sensitivities, the causes of changes in the response as presented in Table 5-11 will be used. The table also gives an indication of the expected magnitude of the response. Next to the direct effects of input parameters shown in Table 5-11, the effects may cascade through the evaluations and iterations. For instance, changes in design variables will consecutively affect many properties and performance parameters, which in turn may change the relative importance of parts of the LPC for the next iteration. The magnitude of these indirect changes can be assessed by following the path of the effect and using Table 5-11 for each step. However, in most cases only the direct effects will be discussed.

The next sub sections discuss the response per discipline and for the system level parameters. Each sub section follows the same structure. First, the place of appearance of input parameters in the models and design algorithm of the discipline is used to determine ‘at a glance’ whether design variables, properties and performance parameters are expected to respond. Then, a closer look at the models and algorithm is given to analyse the ‘direction of change’. Finally, it is assessed whether the ‘relative magnitudes of change’ correspond with the expectations from the right hand column of Table 5-11.


5.3.2 Support structure parameters

At first glance

Figure 5-5 shows the response of support structure parameters. These parameters do not change for many cases. They only respond to changes in environmental conditions and RNA loads, as well as geometric parameters of the RNA. The only parameter that is optimised for the support structure is the tower length, which influences the hub height. The hub height always ends up at its constrained lowest value of 60.8 m. The expectation that optimisation of tower length would lead to the constrained lowest value is also mentioned in Section 4.5.2. The optimisation of hub height is expected to become important in cases with very high costs of other disciplines. Then, the benefit of higher energy yield with increasing hub height may outweigh the relatively low cost increase of the support structure. Indeed, a change in RNA price by a factor 10, relative to the reference price, results in an optimised hub height of 79.5 m. In case of a wind farm of two rows and two columns the hub height becomes 66.9 m.

Consequently, in the sensitivity analysis the design of the support structure is only affected by the constraint functions. Changes in other parts of the wind farm design do not affect support structure design through their effect on the objective function evaluations. Thus, parameters that do not appear in the constraint functions of the support structure design process have no effect on these parameters.

<table>
<thead>
<tr>
<th>Place of appearance of input parameter and affected output</th>
<th>Example</th>
<th>Expectation of magnitude of response</th>
</tr>
</thead>
<tbody>
<tr>
<td>KBE rule that determines a design variable</td>
<td>yaw bearing diameter directly changes tower top diameter</td>
<td>large – design variable is explicit function of input</td>
</tr>
<tr>
<td>model that determines a property or performance</td>
<td>average wind speed directly changes energy yield</td>
<td>large – property or performance is explicit function of input</td>
</tr>
<tr>
<td>constraint that drives a design variable</td>
<td>tower length is driven by rotor diameter, through constraint on hub height</td>
<td>fairly large – functional constraints often have non-zero derivative w.r.t. design variable</td>
</tr>
<tr>
<td>part of objective function that is re-evaluated in optimisation of a design variable</td>
<td>distance to grid connection point affects trade-off between costs and losses in transmission cable</td>
<td>moderate – original objective function had zero derivative w.r.t. design variable</td>
</tr>
<tr>
<td>part of objective function that is re-evaluated outside optimisation of a design variable</td>
<td>RNA purchase price changes relative importance of cable costs in optimisation of spacing</td>
<td>small – original objective function had zero derivative w.r.t. design variable and the re-evaluated part of the objective function is not affected</td>
</tr>
</tbody>
</table>
Directions of change

Hub height increases when the rotor diameter is increased, because that increases the constrained value of the tower length. Hub height is not affected by the change in wave height, because in the current case the active constraint is the clearance between the blade tip and the water, rather than the clearance with the platform.

Pile diameter increases for increasing wave height, water depth, RNA load and rotor diameter. All four changes lead to larger bending moments in the pile. The first three changes cause higher external loading. The increase in the rotor diameter increases the lever arm of the RNA loads, due to the increase in the hub height. The pile diameter decreases when the yaw bearing diameter decreases. The smaller yaw bearing leads to lower wind loading on the top segments of the tower and therefore a lower bending moment in the pile.

Pile mass changes correspond with pile diameter changes. In addition, the pile mass increases when the soil becomes weaker, since it requires a larger pile length. When the average wind speed decreases, the extreme wind speed also decreases. This leads to lower extreme wind loading and therefore a smaller pile diameter and lower pile mass. The change in pile diameter in this case is smaller than the resolution of the shown data.

Increases in pile diameter lead to decreases in tower mass and vice versa. Larger pile diameters lead to larger tower diameters, because of the KBE rules that are applied. When the yield stress dominates the design, the wall thicknesses may consequentially get smaller and result in a lower mass. This is apparently the case for the tested conditions. For larger increases in pile diameter the buckling stress may become...
dominant, causing the wall thicknesses and the masses to grow. This may explain why the mass of the transition piece increases when the rotor diameter increases. Figure 5-6 supports this rationale. It shows the changes in pile diameter, wall thicknesses and masses of the support structure for different values of the drag coefficient of an idling rotor. The drag coefficient changes the loads on the rotor-nacelle assembly during extreme wind speeds. At lower drag coefficients the loads during extreme wind speeds are presumably smaller than the loads during operational conditions. Hence, the support structure doesn’t respond to changes for the first three points in the figure. After this, monopile diameters go up as expected. Initially, the wall thickness and mass of the tower and transition piece go down, as the monopile diameter goes up. However, this downward trend is small and reverses after further increase. This is consistent with the previous discussion. The monopile wall thicknesses don’t decrease, because they are connected to the monopile diameter through a KBE rule that is based on buckling during pile driving.

In the case of the reduction of the yaw bearing diameter, both the tower top diameter and the tower base diameter are reduced. According to the previous analysis, the tower design of the reference is dominated by yield stresses. In that case, smaller diameters imply larger wall thicknesses and larger masses. This is confirmed by the increase in tower mass for this case.

In the case of the rotor diameter increase, the tower mass increases due to the increase in tower length. Similarly, the transition piece mass increases for larger water depths and wave heights, due to increase in its length.

The scour protection changes with respect to changes in the environmental conditions as expected. Larger waves lead to larger friction forces on the rocks, while deeper water leads to lower wave motions at the seabed and thus lower friction. There is a small response of grain size to the increase in pile diameter, because this affects the flow

![Figure 5-6](image_url)

*Figure 5-6 Wall thicknesses in the support structure as a function of the drag coefficient of the idle rotor*
acceleration around the pile. For larger piles the Keulegan-Carpenter number becomes smaller and in the current case this reduces the amplification of water particle motion.

**Relative magnitudes of change**

Changes in length generally dominate the changes in masses of components of the support structure. Next to that, the increase in rotor diameter has a large effect on most parameters, due to the increase in lever arm of the aerodynamic loads. For the monopile mass, the second largest influence is that of the RNA loads, also through the increase in bending moments. The effects on tower mass are generally smaller, because the increase in its diameter opposes the negative effect of an increase in bending moments, for small variations.

As expected, the size of the rocks for scour protection is mainly influenced by the wave height.

5.3.3 **Maintenance parameters**

**At first glance**

Figure 5-7 shows the response of maintenance parameters. The number of shifts per day doesn’t change and the number of crews per shift changes only for the two cases where the farm size is decreased. Both parameters can only have integer values and are therefore not sensitive to small changes in the input parameters.

The waiting time before ordering lifting equipment changes for all cases. The optimisation of this parameter is unconstrained, so it responds to changes in relative importance of terms in the objective function only. Since the design variables of the maintenance discipline don’t change for most cases, the waiting time apparently

![Figure 5-7 Sensitivity of maintenance parameters](image-url)
responds to the effect that other disciplines have on the objective function. This influences the trade-off between additional costs of mobilisations and additional availability, when lowering the waiting time.

The availability changes substantially for changes in accessibility, distance to the harbour, failure rates and service demand. These parameters appear directly in the evaluation of availability. The availability is also influenced indirectly by the changes in the optimised waiting time before ordering lifting equipment. This causes the noticeable change in availability for the case where the price of the rotor-nacelle assembly is increased.

**Directions of change**

The simplified model for the determination of the minimal number of crews, introduced in Section 5.2.4, gives a number of 4.24 crews for the reference farm. This number is sufficiently far from a transition to another number of crews to avoid that the number changes for small changes in input parameters. Apparently, only the reduction in farm size has a significant enough effect. This is confirmed by the simplified model, which gives a minimal number of crews of 3.71 and 3.82 for the 7x10 and 8x9 farms, respectively. The other changes are indeed insufficient according to this model, which yields for the other changed parameters: access - 4.85 crews, harbour - 4.45 crews, failure that doesn’t need lifting - 4.35 crews, failure that does need lifting - 4.35 crews and service demand - 4.51 crews.

When the MTBF for failures that don’t need lifting equipment is reduced to 2,000 hours, the simplified model gives a minimum crew requirement of 5.32 and the number of crews in the emulation is indeed changed to 6. However, in this case the crew is divided into 3 crews during a daytime shift and 3 crews in a night time shift. Apparently, the high probability of failures during the night demands a faster response of the crews. The resulting increase in availability is more important than the additional costs of night time shifts. This division of crews over night and daytime shifts is primarily expected when an even number of crews is needed, since the model assumes that all shifts have the same number of crews. A double shift is not expected when the MTBF for failures that do need lifting equipment reduces. These failures need to wait for lifting equipment and receive crew attention 24 hours per day when the equipment has arrived. Indeed, reducing the MTBF for these failures to 30,000 gives 5.22 crews in the simplified model and 1 shift with 6 crews in the emulation.

All previous numbers indicate that for the tested cases the optimisation of crew deployment always ends up at the minimum required number of crews. The cost of additional crews apparently doesn’t pay off in a sufficiently large increase in availability. In the reference case the downtime due to a waiting list during the steady state is negligible. Therefore, the number of crews mainly affects the downtime that is caused by the waiting list after a storm. This downtime contributes about 10% to the total downtime and therefore the effect of additional crews on availability is too small. A further assessment of the optimisation of the number of crews and the number of shifts is shown in Table 5-12. The MTBF is chosen to give a number of crews in the simplified analysis that is near 95% of the targeted number of crews. The number of crews in the emulation of the initial guess confirms that the targeted number of crews is
the minimum that is needed. The division of crew over two shifts only happens for larger numbers of failures, when 6 or more crews are needed. The number of crews in the optimisation sticks to the minimum, until 9 crews are needed. Apparently, for this many crews the discretisation of the number of crews is no longer keeping this design variable at a bound optimum point.

The waiting time before ordering lifting equipment goes down for the case where the MTBF for failures that need lifting equipment decreases. In this case the probability that another failure occurs during the waiting time is larger. Therefore, it is more likely that more repairs can be done per mobilisation, also for shorter waiting times. The waiting time also goes down for the changes in accessibility, distance to the harbour, failure rates and service demand. These changes lead to a large reduction in availability, which is combated by the reduction in waiting time. As expected, this compensation is not enough to avoid a net decrease in availability. The waiting time also reduces for one of the two smaller wind farms. This is not directly in line with expectations. Due to the lower number of turbines, the probability that more failures can be repaired during one mobilisation decreases, which would expectedly lead to longer waiting times. Apparently indirect influence factors, such as the changed project cost, maintenance costs and annual energy yield per turbine, play a more important role for this farm. Since all changes are so large for these two cases the effect on the waiting time is not further investigated. In most other cases the waiting time responds to changes in project costs as expected, meaning that if project costs go up the waiting time goes down to get higher availability. This is clearest for the case where the RNA price is increased. This effect doesn’t happen in the case of a larger rotor diameter. In this case the hub height increases, which increases the rental costs of lifting equipment. This has an increasing effect on the waiting time, to increase the probability of repairing more failures with one of the now more expensive mobilisation.

**Relative magnitudes of change**

As discussed extensively, the number of shifts and crews is only influenced by the size of the wind farm, for the chosen cases. This matches the expectations.

The largest effects on the waiting time before ordering lifting equipment appear in response to changes in project costs, such as for price of the RNA, higher waves and larger distance to the grid connection point. As discussed, the waiting times respond only to changes in the objective function. Hence it can be expected that project costs have a dominant effect. The increase in project costs for a change in rotor diameter is
almost completely offset by the increased cost of lifting equipment for higher lifting height and therefore less visible. The effect of change in the MTBF of failures that need lifting equipment is also large. This effect is twofold, since it is a response to the increase in maintenance costs, as well as to the higher probability of multiple repairs in one mobilisation.

The failure rates and service demand have expectedly the largest effect on the availability, particularly those for failures that need lifting equipment. Next to that, the large effect of accessibility and distance to the harbour is expected, since these parameters directly affect downtime.

5.3.4 Layout

At first glance

Figure 5-8 shows the response of layout parameters. Row and column spacing respond to all changes in input parameters. These parameters are the result of an unconstrained optimisation and are therefore sensitive to any input that affects the objective function. The spacings, area used and wake efficiency mostly follow the same pattern. Larger spacings evidently lead to larger usage of space, as well as higher efficiency. The pattern is broken for the two smaller wind farms, because here the number of turbines also affects the used area and the efficiency. The pattern is also broken for the change in average wind speed, thrust coefficient and rotor diameter. These parameters also directly influence the wake efficiency.

Directions of change

The change in spacing for the two smaller wind farms is not as expected, in first instance. The farm of 7x10 turbines has fewer turbines in a row than the reference wind

Figure 5-8 Sensitivity of layout parameters
farm. Therefore, wake losses for wind directions parallel to the row become smaller and it is expected that the spacing in the row becomes smaller. Apparently, this direct effect on spacing is overruled by the indirect effect of one of the many other changes in this wind farm. The wind farm with 8x9 turbines has fewer turbines in a column than the reference wind farm and therefore a decrease in spacing in the column is expected here. Again, there appear to be larger indirect effects.

The only other input parameters that directly appear in the optimisation of layout are the power, the average wind speed, the thrust coefficient and the rotor diameter. The primary effect of the change in power is that the power at each wind speed and hence the annual energy production are multiplied with a constant factor. This would not affect the layout. However, the decrease in power also changes the design of the electrical infrastructure, which has an indirect effect on the layout optimisation. The cost reduction of the infield cables drives the optimisation to slightly larger spacings. Changes to the other three parameters all increase the wake losses. In case of a lower average wind speed the wind turbines operate more often at lower wind speeds, where the thrust coefficient is high. This causes high wind speed deficiencies. Furthermore, the wind speed deficiency results in more loss of power when it affects turbines that operate below rated wind speed. This also happens more often when the average wind speed is lowered. The increase in thrust coefficient leads to a larger wind speed deficiency at all wind speeds. Finally, the increase in rotor diameter causes larger wakes, with a higher frequency of overlapping with a downwind rotor area. Furthermore, the larger rotors reduce the wind speed over a larger area and it consequently takes longer recuperation distances. The expected and observed effect of the increase in wake losses is a further separation of the wind turbines.

The other parameter variations have indirect effects on layout. Mostly, these parameter variations lead to a general cost increase, which is combated by a higher spacing that leads to higher wake efficiency. The changes in accessibility and distance to the harbour deviate from this expected response. The spacing in the column does increase, but the spacing in the row decreases. Perhaps this is a balance between increasing wake efficiency and reducing travel time of maintenance personnel in the wind farm.

For two reasons the sensitivity of layout parameters is further analysed. First, some of the previously discussed effects may be correct, but were not expected. Second, it is expected that the response may not be smooth, due to the nature of the wake loss analysis. Wake losses are very sensitive to the wind direction. When the wind aligns with a line of turbines, the losses are very high, while the losses become very small when the wakes can pass between downwind turbines. This behaviour of wakes is emphasised by Jensen’s model, which has a discontinuous transition between wake flow and undisturbed flow. The wake effect is sampled for wind directions with a step size of 2.5°. Some ratios between spacings in row and column align the turbines along some sampled wind directions, while small changes in the ratio avoid this alignment. It is expected that the optimiser will avoid the ratios that align the turbines with the sample directions.

To test the smoothness of the response of layout parameters, the RNA purchase price is gradually increased from the reference value to the value used in the sensitivity study. This approach ensures that the effect on layout is only indirect and it is expected to lead
to an increase in spacing and wake efficiency. The results are shown in Figure 5-9. The overall trend is indeed one of increase, but it is clear that the response is far from smooth. The effect of the erraticness on the LPC is below the general increase of this parameter. Nevertheless, there may be situations where this character of the response is undesirable.

**Relative magnitudes of change**

The size of the wind farm, the average wind speed, the thrust coefficient and the rotor diameter have a direct effect on wake losses and therefore result in the largest responses. The other effects are indirect and therefore lead to smaller responses.

5.3.5 **Electrical system**

**At first glance**

Figure 5-10 shows the response of electrical system parameters. The voltage level and cable cross-sectional area of both the infield and the transmission cables respond to all changes. The voltage level is an optimised parameter that is unconstrained, apart from the bounds on the search region. The cross-sectional area is constrained by the maximum temperature in the cable, but the solution for the reference wind farm is a free point in the design space for both cables. Therefore, these parameters are susceptible to any change in the objective function contributions.

The voltage level of the transmission and the transmission cable cross-section show a highly correlated response. Both parameters lead to a trade-off in cable costs and losses, which have balanced gradients for the reference wind farm. Any parameter that offsets this balance because it changes a part of objective function that is re-evaluated outside optimisation of the electrical system has a similar effect on voltage and cable cross-section. Hence, the response of these parameters is highly correlated. For instance, an

![Figure 5-9: Normalised layout parameters and LPC as function of RNA purchase price](image)
increase in other costs will lower the weight of cable costs. Hence, both an increase in voltage level and an increase in cross-sectional area will decrease the LPC through the reduction in the losses, which consequently has a larger effect than the increase in costs. Variations in the grid frequency and in average wind speed and to a lesser extent variation in grid distance give a visible discrepancy between the transmission cable parameters. These parameters affect cable costs and losses directly and in an unequal way.

Similar effects occur in the optimisation of infield voltage level and cross-section. However, unlike the transmission cable length, the infield cable length changes for most cases as a consequence of the changes in spacings. The different cable length changes the balance between cable costs and losses in different ways for the optimisations of voltage level and cross-sectional area. Therefore, the response of the infield cable parameters is less correlated.

**Directions of change**

Because the length of the transmission cable only changes for one case, the analysis of the response of voltage level and cross-sectional area of this cable is simpler than that of the infield cable. For the transmission cable the effect of voltage level and cross-sectional area on the LPC can be assessed based on consideration of their effects on losses and costs per meter. For the infield cable the effect of cable length comes into play, increasing the number of parameters that change the LPC. Therefore, first the directions of change of the transmission cable are discussed. Thereafter, the effect of changes in infield cable length are discussed and added to the ingredients of the discussion of the transmission cable.

*Figure 5-10 Sensitivity of electrical system parameters*
The voltage level and cross-sectional area of the transmission cable go down when the largest effect of a changed input variable is a reduction in the maximum power transported through the cable. This is the case for the two smaller wind farms and for the turbine with the lower rated power. In these cases, the active currents in the reference transmission cable reduce and therefore the losses reduce. The optimiser responds by lowering the voltage and cross-section. A similar effect happens when the average wind speed is decreased. Figure 5-11 shows the efficiency of the transmission cable of the reference wind farm as a function of wind speed. At very low wind speeds the no-load losses dominate the efficiency and at higher wind speeds the loaded losses dominate. In between, there is a maximum efficiency. When the average wind speed reduces, the transmission cable is operated more often at higher efficiency. This also leads the optimiser to reduce voltage and cross-section.

The increase in grid frequency increases the reactive currents and the dielectric losses. Since these are proportional to the voltage and the square of the voltage, respectively, the optimiser responds with a reduction on voltage level. In addition, the cross-sectional area of the cable increases to get the losses down.

The reductions in grid voltage and generator voltage increase the cost of the onshore transformer and turbine transformer, respectively, because these costs are a function of the ratio between input and output voltage. The response is a reduction in transmission voltage for the first case and a cascaded reduction of infield voltage and transmission voltage for the second case, to combat this effect. To keep the losses down, the cross-sectional area of the transmission cable increases.

The effect of the change in thrust coefficient on the transmission cable is very small and indirect. The voltage level and cross-sectional area increase a little, most likely to counteract the increase in wake losses.

The remaining input variables that are varied increase the other cost contributions,
which reduces the relative importance of transmission cable costs. This enables an increase in voltage and cross-section to reduce the losses. This expected response is clearly visible for purchase price of the RNA, increase in rotor diameter and increase in wave height, but also happens for the other variables.

As mentioned above, the analysis of the response of infield cable design is complicated by the changes in cable length. The response of transmission cable design to a change in grid distance includes the effect of changed cable length. A first order assessment suggests that both voltage level and cross-sectional area would increase when cable length increases. An increase in cable length has a near proportional effect on both the losses and the costs of the cable. Since the losses directly affect the denominator of the LPC, while the cable costs are weighted against other costs in the numerator, the increase in loss dominates the offset balance. This will be compensated by an increase in voltage and cross-section. This can indeed be observed for the response of transmission cable parameters to the increase in grid distance. However, the results suggest that an increase in length of the infield cable leads to a higher infield voltage level but a lower cross-sectional area. Particularly the response to changes in average wind speed, the thrust coefficient and the rotor diameter show this. The increase in voltage level reduces the active currents and this enables a reduction in cross-section to reduce the costs. Despite this being a reasonable response, it is not consistent with the transmission cable response to change in length. It seems that several effects contribute to the response and it is not clear which effects dominate in each case. The analysis of the operation of the cables in the reference wind farm, shown in Table 5-5 of Section 5.2.3, shows that the relative magnitude of the reactive currents is larger in the transmission cable than in the infield cable. This could be the cause of the difference in response. The reactive currents increase with increasing voltage and this negative effect seems to suppress the increase of voltage level in the transmission cable. The effects of changes in cable length have not been further assessed, but it is assumed that it leads to increase in voltage level and decrease in cross-sectional area of the infield cable. This effect of cable length will be in competition with the effects that were discussed for the transmission cable.

Indeed, the infield voltage level and cross-sectional area response is consistent with the previous suggestion. When the row and column spacing are almost the same as in the reference wind farm, the infield cable parameters have similar response as the transmission cable. The larger the spacings differ, the more the cable length effect is seen. Particularly the change in spacing in the row shows this effect, since this spacing has the largest effect on cable length. Larger spacing leads to an increase in voltage level and a decrease in cross-sectional area that is superimposed on the effects that are seen in the transmission cable. This is particularly clear for the 8x9 wind farm and the changes in average wind speed, the thrust coefficient and the rotor diameter. Whether or not the change in cable length outweighs other effects depends on their relative magnitudes. For instance in the case of the changed RNA purchase price the increased cable length does have a reducing effect on cross-sectional area, but not as strong as the increasing effect that is seen for the transmission cable.
**Relative magnitudes of change**

The effect of a change in transmitted power is the most direct and therefore expectedly the largest. The increase in grid frequency and the reduction in average wind speed also directly affect the losses in the cable, but to a lesser extent. For the infield cable the largest effect is seen for the change in generator voltage. The drop in generator voltage directly affects the turbine transformer costs, since these depend on the voltage level ratio. This results in the large reduction in infield voltage level, relative to the other effects.

The changes in cable length also have a significant effect, because these directly affect the losses. However, the overall response of voltage level and cross-sectional area is partly counteracted by the increase in cable costs due to the larger distance.

The other influences are smaller, because these act mainly through a new balance between different cost contributions. The effect of change in RNA purchase price is nevertheless clear, because this is a relatively large change.

5.3.6 **System level parameters**

**At first glance**

Figure 5-12 shows the response of system level parameters. These parameters inevitably respond to all changes. For the two smaller wind farms all parameters go down. For the other changes in input the project costs and O&M costs go up, apart for the case with the lower power. The LPC goes up in all other cases. The annual energy yield shows both positive and negative changes.

![Figure 5-12 Sensitivity of system level parameters](image-url)
**Directions of change**

The O&M costs reduce for the smaller wind farms as expected, since the number of turbines reduces. For the other cases, the change in O&M costs is caused by a combination of the effect of wind farm size (through bottom lease costs), annual energy yield (through grid connection costs) and waiting time before ordering lifting equipment (through rental costs). For the cases with lower MTBFs there is also an increase in consumables and spare part costs and for the case of the increased price of the RNA the insurance costs are higher. The numerical results of the changes in O&M costs are in line with hand calculations that are obtained when each of these influence factors is given an appropriate weight.

Changes in project costs are also the cumulative effect of many changes in the contributions for this parameter. Generally, the project costs were expected to increase, apart for the two smaller wind farms. Most parameters have a direct effect on the design and costs of a component, through their appearance in the cost evaluation, a constraint or KBE rule. Examples of such parameters are the distance to the grid and the wave height. Some parameters reduced the efficiency of the system, which was compensated by investing in improvements. An example of this is the reduction in thrust coefficient, which increased the wake losses. This was combated with larger spacing and thus longer cables. The project costs are reduced for the case with the lower power of the turbines. The lower power could be transported through cheaper cables and it wasn’t possible to make up for the loss in power by investing in improved efficiency of the electrical system.

The annual energy yield goes down for all changes that have a direct negative influence on the electrical efficiency, the array efficiency or the availability. Examples are the response to changes in accessibility and distance to the grid. The annual yield evidently also goes down when the power of the wind turbines and the number of turbines are reduced. In the other cases the effect on annual energy yield is marginal or positive. In these cases the optimisation combats the negative influence of changes in costs through increase in electrical efficiency, array efficiency or availability.

The LPC was expected to increase for all cases. As mentioned in Section 5.3.1 the parameter changes were chosen to be unfavourable for the wind farm. However, the LPC decreases for the two smaller wind farms. Table 5-13 shows the percentual changes of annual energy yield, project costs and O&M costs per turbine. For the 8x9 farm the new spacing and the relatively larger number of turbines in the perimeter of the farm resulted in a higher energy yield per turbine, but not so for the 7x10 farm. Nevertheless, the change in annual energy yield doesn’t compensate the change in project costs per turbine, which go up in both cases. The reduction in LPC is caused by the reduction in O&M costs, which is in turn caused by the reduction in the number of crews. The discontinuous drop in the number of crews per shift results in a disproportional cost benefit for the smaller wind farms. In other words, the crew deployment in the smaller wind farms is more efficient, while the crews in the reference wind farm have a low occupancy rate. Using the straightforward assessment of the numbers of crew needed, as introduced in Section 5.2.4, the reference wind farm needs 4.24 maintenance crews, the 7x10 farm needs 3.71 crews and the 8x9 farm needs 3.82
crews. This simplified analysis shows that about three quarters of one crew is idle in the reference farm, while only about one quarter is idle for the other two wind farms.

The effect of discretisation of the number of crews on the LPC is illustrated in Figure 5-13. This figure shows LPC as a function of the number of columns of a wind farm with 4 rows. Each extra column of turbines corresponds with a need for approximately 0.212 crews, according to the straightforward model. Therefore, after each increase of the farm size with four or five columns the tool deploys an additional crew. This causes the local increases in LPC in the furthermore gradually descending curve. These discontinuities may be undesirable when using the tool.

**Relative magnitudes of change**

The relative magnitude of the changes of system level parameters is not analysed in detail, because there are so many contributing factors. Nevertheless, it is noted and understandable that the average wind speed and power have a large effect on annual energy yield and thus on LPC. The effects of project costs and O&M costs on LPC are second and third to this, because of their relative importance in the equation.

### 5.4 Practical performance tests

#### 5.4.1 Speed and improvements per process

The wind farm design emulation is intended to be used in the iterative loops of a rotor-nacelle assembly design process. Therefore, it will be run many times. The speed of the

| Annual output per turbine [%] | 0.3 | -0.2 |
| Project cost per turbine [%]  | 1.2 |  0.4 |
| O&M cost per turbine [%]     | -2.9| -4.5 |

<table>
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</tr>
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<td>10</td>
</tr>
<tr>
<td>30</td>
<td>9</td>
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*Figure 5-13 LPC as a function of the number of columns of a wind farm with 4 rows*
emulation is evaluated to determine whether waiting times for results are acceptable. Particularly for the prototype the waiting times should be small, to have a low demand on the time of the persons that will test the tool. The evaluation is done for an Intel Xeon E3-1245 (3.30 GHz, 8MB, QC), using only one core. This is considered representative for the users.

As a general measure of the effectiveness of the optimisations, the improvements in the objective function during the execution of the processes are evaluated. The value of the objective function after the initial guess is taken as a reference. Since the objective function is minimised, reductions are presented as positive values for the improvement.

The duration and the improvements per process are logged for 20 cases. The first case is the emulation of the Horns Rev wind farm and the 19 other cases are the variations for the sensitivity study shown in Table 5-10. The cases for the two smaller wind farms in this table are not included. The sequential scheme of the emulation that is illustrated in Figure 4-11 shows which processes take place during the emulation. The total duration is divided into contributions according to the processes that are shown in that scheme. Two divisions are used. One divides the contributions per discipline. This division separates the duration of the first evaluation of the objective function, since that is not associated with any of the disciplinary optimisations. The other division shows the contributions of the initial guess and those of each pass of the optimisation loop of the four disciplines. An overview of the results is given in Table 5-14.

The average duration of 7½ minute is considered to be acceptable. It is clear that by far the largest time is spent on the layout optimisation. The improvements are evident, but not very large. Apparently, the initial guess is rather close to the optimum. The design variables that get an initial guess are the hub height, the spacings, the transformer winding ratios, the infield and transmission cable conductor diameters, the number of shifts per day, the number of crews per shift and the waiting time before lifting

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**Averages per discipline**

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<td>Maintenance</td>
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<td>0.64</td>
</tr>
<tr>
<td>Layout</td>
<td>444.2</td>
<td>1.05</td>
</tr>
</tbody>
</table>

**Averages per phase**

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial guess</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>Optimisation pass 1</td>
<td>352.6</td>
<td>2.80</td>
</tr>
<tr>
<td>Optimisation pass 2</td>
<td>86.7</td>
<td>0.06</td>
</tr>
<tr>
<td>Optimisation pass 3</td>
<td>12.4</td>
<td>0.0004</td>
</tr>
</tbody>
</table>
equipment. All other design variables get an initial guess that is determined in the same way as during the optimisations. The initial guesses of the hub height, the number of shifts per day and the number of crews per shift are at their minimum constrained values and these have been shown to be the same in the optimised results of these cases. Hence, the improvement in the support structure discipline is negligible. The improvement in the maintenance discipline is small, since only the waiting time before ordering lifting equipment gets an optimum that differs from the initial guess. Expectedly, the LPC is not very sensitive to this. The remaining optimised variables are from the disciplines ‘Electrical system’ and ‘Layout’ and have the largest effect on the improvement during the optimisation. The improvements after the first pass of optimisation of the disciplines are relatively small. These improvements are the insensitive responses to changes in the relative importance of different contributions to the objective function.

5.4.2 Speed and improvement as function of wind farm size

The previous section shows that by far the largest time is spent on the layout optimisation. This is caused by the duration of the wake efficiency evaluation. Most of the implemented algorithm for the wake evaluation has a computation burden that is proportional to the number of turbines, $N_t$. However, for part of the algorithm the computation burden is $O(N_t^2)$. Therefore, the total duration of the emulation is given as a function of the farm size in Figure 5-14. Indeed, duration of the emulation increases rapidly when the number of turbines increases. The figure can be used as a guideline when choosing the farm size of the emulations.

The farm size is also expected to have a large effect on the total improvement that is achieved during the optimisation. The initial guesses of for instance the voltage levels and spacings are based on current typical wind farm sizes of the order of magnitude of 100 turbines. Figure 5-15 shows the improvement as a function of farm size. Indeed, for very small and very large farms the improvement gets larger and the initial guess is

![Figure 5-14 Duration of the emulation as function of farm size](image)
apparently not so good. This indicates how much more worthwhile the optimisation is for cases that differ from current day practices. If the initial guess is considered to be acceptably well for wind farms that are similar to the state-of-the-art, the optimisation becomes more and more necessary when deviant wind farms are explored.

### 5.4.3 Stability of finding a solution

Chapter 4 pays attention to the set-up of the optimisation and root finding algorithms, to ensure that the tool would be able to find a solution in most conditions. Indeed, all of the 100 optimisations and 20 additional initial guesses performed for the earlier discussions didn’t lead to instability in solving the design problem. However, many of these cases were similar to emulation of the Horns Rev design. In this section the stability of the emulation under more extreme variation of the inputs is tested. The input parameters that are selected for these variations are similar to those of the sensitivity analysis in Section 5.3.1. The variations are shown in Table 5-15. Although the values for the extremes are chosen to be beyond normal variations, they are still imaginable. For instance, a distance to the grid or yaw bearing diameter of zero is not tested.

Two cases failed in this test. The minimum value of the grid voltage and the minimum value of the generator voltage didn’t lead to a design solution.

For the low grid voltage, the optimisation routine of the transformer winding ratios failed. As mentioned in the discussion of this routine in Section 4.5.3 the setting of the boundaries for this optimisation is a balancing act. Indeed, the boundaries that are chosen are insufficient to include a transformer that steps up the voltage from the grid voltage to the transmission voltage of the initial guess. In other words, the initial guess of the electrical system is not a feasible design of the optimisation algorithm. Therefore, this is an inappropriate starting point for the algorithm and it returns with a failure. When the upper bound of the onshore transformer winding ratio is increased from 5 to 8

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Figure 5-15 Improvement from optimisation after initial guess as function of farm size

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the initial guess becomes a feasible solution. Indeed, this resolved the problem. However, it is not guaranteed that this doesn’t lead to other problems caused by the balancing act. Therefore, the upper bound is kept at 5, which is still considered reasonable for normal grid voltages.

The low generator voltage caused instability in the interpreter. The optimisation of the electrical system failed after several iterations, probably due to an overflow error. Intermediate results showed very high values of the objective function, which originated from high turbine transformer costs. These high costs are a consequence of the large transformer winding ratio needed to obtain the low voltage level of the generator. This winding ratio was beyond the range of validity of the transformer cost model. The problem could be resolved by limiting the turbine transformer costs or setting the initial guess of the infield voltage at 20 kV instead of 45 kV. Since the problem didn’t occur for a generator voltage of 200 V and such low voltages are unlikely in Multi MegaWatt turbines, no changes have been made to the algorithms.

5.5 Conclusions about suitability of the tool

To start with the practical performance, the tool has been demonstrated to be satisfactory. The stability has proven to be good, despite the numerous optimisation and root-finding problems in the design algorithms. Normal input data are expected to result in design solutions. The user has to be aware that even though the tool may generate a
solution, it may not be the best wind farm design. For some input data different concepts and configurations may be more optimal. Furthermore, solutions of the tool may have dimensions that do not correspond with current manufacturing capabilities. It is recommended to check the engineering results of the tool as regards reasonability of the solution.

Computation times are short enough to use the tool in design iterations. The assessment of wake losses and consequentially the optimisation of the layout dominate the time needed. When the user has no reason to assess performance of the RNA in larger wind farms, it is recommended to avoid unnecessarily large numbers of turbines. The sample rate of wind directions in the assessment of wake losses is set at a trade-off between computation times and accuracy. When a smoother response of the layout optimisation is needed, the resolution of wind direction can be set finer. A coarser resolution is not recommended.

The absolute values of the results are reasonable, but have to be considered with care. Differences can often be explained, for instance by differences in the configuration, differences in the constraints or differences in the design philosophy. An example of the difference in configuration is the lack of an onshore transformer in some realised wind farms, which forces the transmission voltage to the level of the grid. An example of a difference in the constraints is the existence of restrictions on the usage of space in some realised wind farms, which affects the layout. An example of the difference in philosophy is the use of standard electrical cables in realised wind farms, which allows only discrete changes in the voltage levels. Notwithstanding the explanations, there remains a difference between the realised wind farms and the emulated designs.

The differences in the design results as well as the limitations in the cost models lead to a final inaccuracy in the estimated investment costs and LPC in the order of 20%. Some of the inaccuracy is due to incorrect input data, caused by lack of information. Particularly the good correspondence of engineering results and investment costs for Horns Rev is a good sign of the performance of the tool. This wind farm has the most similar configuration and for this wind farm the most representative inputs were used. For use of the tool to optimise the RNA, the absolute values are not as important as the relative contributions that determine the weight of different aspects in a trade-off. The distribution of investment costs over different contributions is shown to be sufficiently well represented in the tool. A particular point of attention is the high maintenance cost, even though this is likely associated more with the choice of input data than with the model. The tool also shows significant differences with reality for the layout, probably due to the assumed bottom lease costs and the lack of constraints on usage of space in the tool. Analysis of these differences doesn’t identify the cause, but confirm that the tool designs the layout as expected. Although the high O&M costs and differences in layout may affect the numerical results of trade-offs for RNA parameters that are made with the tool, they are not expected to affect the functionality that users will experience during the test of the tool.

Of primary importance for the use of the tool to make trade-offs in RNA design is its response to changes in input parameters. Both the differences observed between the three emulated wind farms and the sensitivity study provide confidence in this aspect of the behaviour of the tool. The discretisation of the number of crews per shift is the
largest threat for the use of the tool. It causes discontinuities in the response of the LPC to changes in input parameters. It is recommended to check the results for a change in the number of crews, which reveals when the LPC exhibits a stepwise response. Furthermore, it reduces the sensitivity of the LPC to changes in parameters that affect the number of crews. For instance, the positive effect of an increase in reliability may be insufficiently represented in the tool when the number of crews remains constant. Until this behaviour of the tool is improved, it is recommended to bear this in mind when interpreting the results. The tool also shows a little erratic response of spacing, due to wind direction sampling in wake loss evaluation. However, the consequence of this on LPC is small enough for preliminary design activities and thus much less a threat to utility of the tool. It is considered small enough for the use of the tool in the current research.
6 Validation of the utility of design emulation

6.1 Purpose and methods of validation

6.1.1 Detailing the hypothesis for the created instantiation

Section 3.5.2 provides two axioms on which the design theory of emulated design collaboration is based. These axioms state that collaborative design gives better subsystem solutions and that these can be equalled with perfect emulation of collaboration. Since these axioms cannot be tested in a practical situation, the section formulates a proposition that can be tested:

*There exists an application for which the use of emulation of the external design processes based on the guidelines of this theory provides utility, despite its reduction of scope and imperfections.*

The previous chapters describe an emulation tool and its application to optimise the main parameters of a rotor-nacelle assembly for offshore wind farms. The utility of this instantiation of the theory can take several forms. The types of utility that are expected in this case are:

- to provide better results than existing methods
- to provide better argumentation for decisions
- to need fewer resources than existing methods
- to work faster than existing methods

It is noted that all forms of utility are expressed in a relative sense, without actually specifying the reference. The methods that are currently used are different for different companies, but the proposition states that the proposed new method has advantage over any of these. This formulation is chosen to get the proposition as close as possible to the two axioms. The formulation of the utility is neither precise in specifying the reference method, nor in articulating how much the performance is improved and why. Besides validating the utility on this high level, the results presented in this chapter aim at exploring how these elements of the proposition can be further detailed and quantified. Furthermore, the instantiation of the tool is just a prototype of an immature information
system and therefore the focus of the validation is more on qualifying utility than on quantitative performance.

It is also noted in Section 3.5.2 that failure of an instantiation to show utility does not falsify the general proposition. If this failure can be associated with imperfections in the instantiation, then it may be worthwhile to correct these in future prototypes. Therefore, the results of the validation presented in this chapter also aim at identifying possible imperfections.

6.1.2 Introduction to the three types of validation applied

There are several methods to establish the utility of the instantiation. The introduction of the validation activity in Section 2.2.3 mentions three methods that are identified earlier:

▪ case studies – in-depth study of the artefact in a business environment
▪ controlled experiments – study of qualities of the artefact in a laboratory set-up
▪ informed argument – building a convincing argument for the artefact’s utility

Since these three methods cover a variety of validation activities no additional methods are searched. Most attention is paid to the case studies. Users of the design method in a business environment have better understanding of their needs and can provide a more independent opinion than the creator of the method. This should mitigate the issue pointed out by Caplinskas and Vasilecas that “one of the most serious dilemmas in constructive research is the scientist’s ability to maintain a neutral, even critical, attitude”. However, the expectations about merging the design method in the business environment should be realistic. The use cases with the tool are tested by industrial engineers who have experience with wind turbine design, but these tests are not part of a running turbine design process. The tests are performed separate from industrial activities, because:

▪ merging the method in running processes of several companies leads to planning difficulties, because the method applies to a particular phase of a lengthy process
▪ companies may be reluctant to accept the risks of adopting the premature use cases and tool in regular work
▪ full deployment of the use cases asks for more effort of the companies than a concise test program, which can be performed at times that do not interfere with daily activities.

Despite the possible bias of the creator, the author also validated the design method by informed argument and controlled experiments. The informed argument focuses on substantiating that wind turbine designs are sub-optimal due to insufficient collaboration with wind farm designers and that wind turbine design choices have enough effect on the design of other wind farm elements to expect benefit from wind farm design emulation. The controlled experiments demonstrate the use cases and quantify some of the aforementioned effects. The demonstration of the use cases also provides an illustration of the case studies that are performed in the companies. The content of the use cases performed by the companies are not shown, to protect confidential information of the participants.
The informed argument is given in Section 6.2, followed by the controlled experiments in Section 6.3. The remaining section of this chapter shows the set-up and results of the case study.

6.2 Informed argument: the role of wind farm design emulation

The derivation of the theory in Chapter 3 and the design of the instantiation in Chapter 4 provide several implicit and explicit arguments for the utility of the tool. However, this section focuses on the particular use of emulation of offshore wind farm design for the support of wind turbine design. The developments of the theory and the instantiation are instigated by the observation that rotor-nacelle assemblies are designed long before they are incorporated in the design of an offshore wind farm. The asynchrony of the RNA design process and the wind farm design process is considered to be an indication of lack of collaboration. However, the question whether there is collaboration or not cannot be answered with a qualified yes or no. There is indeed no concurrent design of rotor-nacelle assemblies and wind farms, but there are many mechanisms that provide information about wind farm design to the RNA designer, e.g.:

- conferences, workshops, literature etc. present lessons learnt, case studies and other generic knowledge about offshore wind farm design
- existing wind farms and buyers of rotor-nacelle assemblies provide feedback of past generations of wind farms for the design of future generations of rotor-nacelle assemblies
- the designs of the competition embody the knowledge of the competition and can be copied
- wind turbine manufacturers hire experts with knowledge of the wind farm design process, such as offshore engineers
- cost models of balance of plant, O&M and decommissioning show effects of RNA design changes on the cost of energy

The questions that need to be answered are therefore: are these mechanisms incomplete and can emulation of wind farm design complement them? The answers to these two questions are discussed as regards the first use case of the tool, which is optimising the rotor diameter for a given rated power. This use case is selected for the discussion for two main reasons. First, optimisation of the rotor diameter affects the power density and this is a very fundamental parameter of RNA design. This parameter has large effects on the cost of energy and should therefore receive proper attention from the wind turbine suppliers. If wind farm design emulation helps to complement a lack of collaboration in this area, it is likely that other areas have similar needs. Second, it is to some extent speculative to discuss the lack of collaboration in general terms, but there is some publicly available data to support this discussion. This data will be presented first.

Figure 6-1 shows the power density of offshore wind turbines that are available, built as prototype or on the drawing board. Criteria for selection of rotor-nacelle assemblies on the drawing board are the availability of data and correspondence of the concept with the RNA concept that is used as a starting point for the tool in Chapter 4.
There are many reasons for the scatter and trends in the power density. First of all, power density can be adapted for general wind conditions. Onshore wind turbines that are designed for higher average wind speeds typically have smaller rotor diameter and vice versa. Second, in the upscaling process often only rated power or rotor diameter is increased. An increase in rated power, while keeping the rotor diameter equal, causes the uphill trends of for instance Repower and Bard Engineering. The downhill trend of Areva Wind is an example of increasing rotor diameter for the same rated power. The first two segments of the Vestas curve and the line for GE are the effect of simultaneous changes in rated power and rotor diameter. The zig zag of Siemens is mainly caused by stepwise upscaling of diameter, power and again diameter, with the fourth point being a rotor-nacelle assembly that differs both in rated power and diameter.

Many of the earlier offshore wind turbines have a power density in the range of 400-500 W/m². This is a higher power density than typically seen for onshore turbines. Recently developed rotor-nacelle assemblies show a larger variation, but particularly demonstrate a tendency to smaller power densities. Most of the rotor-nacelle assemblies on the drawing board have a power density between 300 and 400 W/m². The trend to lower power densities seems to be a slow learning effect that apparently corrects the initial increase of power density when rotor-nacelle assemblies were adapted for offshore applications. This would imply that the initial increase might have been a misconception. As stated above, onshore wind turbines tend to have smaller diameters for higher average wind speeds. This knowledge based design rule may have been extrapolated to offshore turbines, causing the increase in power density. However, this
rule isn’t valid for this extrapolation, due to the change in relative magnitude of the different contributions to cost of energy. The later reduction in power density appears to correct for this.

The previous suggestions about the reasons behind the trends in power density are only implicitly derived from the data. There may be other explanations, of which the significance is not acknowledged by this analysis. However, the suggested reasons are consistent with the mechanisms that are given in the bulleted list. Eying the competition may cause inbred misconceptions about the optimality of solutions. This is consistent with the persistence of high power densities in the earlier rotor-nacelle assemblies from different manufacturers. The first three items in the list have long cycle times. They don’t provide immediate feedback in the design iterations of a new RNA model. These mechanisms mainly support design improvements from generation to generation. This is consistent with the slow change of power density. The use of cost models provides more direct feedback to designers, which can be helpful in design iterations. However, such cost models only became available after several years of experience with offshore wind farms. The author first encountered the use of cost models for the design of power density in 2011, for the design of the V164\textsuperscript{13}. These observations about the availability and use of cost models are consistent with the fact that power density only started to reduce recently.

The previous analysis indicates that the lack of information about the effect of power density on costs of offshore wind energy has resulted in sub-optimal design and that the industry has taken a while to catch up. More direct feedback might reduce the time lag for improvements. The use of cost models provides such feedback in recent RNA design processes. This can actually be seen as a rudimentary emulation of wind farm design using highly heuristic models. The cost models are essentially black boxes that do not model the engineering of the wind farm per se, but that do capture the effect of such engineering on costs. However, the cost models often have a limited set of independent parameters. Therefore, they may not sufficiently represent the sensitivity of costs to changes in power density. Furthermore, the independent parameters are not always properly chosen, as argued in Section 4.6.1.

The last part of the informed argument treats whether the emulation does provide the correct sensitivity to changes in power density and whether such sensitivity is expected to have significant effect on the design solution. The effect of changes in power density on the levelised production costs and its components can be traced in Chapter 4, where the design of the tool is presented. This is a two tiered influence. First, the RNA designer must determine how design variables of the RNA should be changed to affect the change in power density and how this affects RNA properties that are used as inputs for the tool. The RNA design variables and properties that are involved and that influence the output of the tool include the rotor diameter, the mass and mass eccentricity of the RNA, the maximal operational thrust and the wind speed at which this occurs, the purchase price of the RNA, the power curve and the thrust curve. Effects of these changes on reliability data and on the costs of spare parts can also be entered in the tool. Second, changes in these input parameters result in changes in the output of the tool. The sensitivity analysis of Section 5.3 shows that the changes in the rotor diameter, the power curve and the RNA purchase price will have the largest effect on LPC. Changes in the maximum operational thrust and the thrust curve have a smaller effect.
The sensitivity study indicates a change in LPC of between 5 to 10% for the most important input parameter variations, when they occur one at a time. This is sufficient reason to further explore the use of the tool.

The previous analysis argues that the current approach indeed leads to sub-optimal design solutions for power density and that the use of the tool may help to make design improvements.

### 6.3 Controlled experiment: Quantifying trade-offs

#### 6.3.1 Introduction to the controlled experiment

Section 4.3.3 specifies four use cases for the tool. Examples of these use cases have been formulated for the controlled experiment. The same examples of the use cases will be applied in the case studies that are discussed in Section 6.4. In the controlled experiment the V80 and the Horns Rev wind farm are used as a reference. The same input data of this rotor-nacelle assembly and wind farm are used as in Section 5.2. The examples of the four use cases are applied to this reference to assess whether the V80 could have been further optimised for a market of users that have similar conditions as those at Horns Rev. After reporting the four use cases, the utility of the tool is discussed.

#### 6.3.2 Use case 1 - Dimensioning the rotor-nacelle assembly

The first use case regards the optimisation of rotor diameter for a fixed rated power. This corresponds with the optimisation of power density, which is discussed in the informed argument of Section 6.2. To assess the effect of rotor diameter variation on levelised production costs, the V80 needs to be redesigned with different rotor diameters. With respect to the use of the tool, this means that new input data for the RNA needs to be generated that is consistent with a change in rotor diameter. The dependency of this input data on the rotor diameter is derived in Appendix G. The model for the dependency of RNA purchase price on rotor diameter contains a parameter, $f_{\text{fixed}}$. This parameter represents that not all costs change when the mass of a component changes as a function of rotor diameter. The nominal value used for this parameter is 0.1. A value of 0.0 means that there are no fixed costs and all cost elements scale proportional to the mass changes. This parameter is used to assess sensitivity of the results to uncertainties in the RNA purchase price model.

Using the models for the RNA input data, the wind farm design has been emulated for various rotor diameters. The resulting levelised production costs are shown in Figure 6-2. The middle line in the figure shows the results with the reference RNA purchase price model, with $f_{\text{fixed}} = 0.1$. If none of the costs are fixed, the line is slightly higher and the lower line shows the results if more of the costs are fixed. As expected, the less the costs scale with mass changes, the higher the optimal rotor diameter and the lower the minimum LPC.

The optimum rotor diameter and minimum LPC have been determined by fitting a 2nd order polynomial through the three lowest points of each curve. The reduction in LPC through diameter optimisation varies between 1.8% and 2.5% for the used purchase
The optimum rotor diameter varies between 89.9 m and 92.5 m, with 90.7 m for the reference model. The power density of the reference V80 is 398 W/m², while the power density for a 90.7 m rotor is 310 W/m². These numbers are in line with the trend in actual wind turbines, as discussed in Section 6.2. These results indicate that the tool provides sufficient information for further optimisation of the rotor diameter, but uncertainty in the purchase price model limits the accuracy.

Intermediate results of the optimisation with the reference purchase price model are analysed to determine the importance of different aspects in the trade-offs and to assess the importance of uncertainty in the cost models inside the tool. Figure 6-3 shows the variation of the contributions to the LPC, as a function of rotor diameter. The three cost contributions increase gradually, although there is a brief halt in the increase of operation and maintenance costs. The investment costs are most sensitive to variation in rotor diameter. Decommissioning costs are also sensitive, but these play a role of less than 2% in the LPC. The annual energy yield also increases gradually, but with reducing slope for increasing rotor diameter. This effect determines that the LPC function has a minimum. The trend in annual energy also shows a break around 95-100 m rotor diameter. This break and the break in the operation and maintenance costs cause the shifts in the LPC curves of Figure 6-2 around 100 m diameter.

Detailed analysis reveals that the source of this effect is the optimisation of the layout. Figure 6-4 shows the trends for spacing in the farm. The spacing in the column drops clearly when the rotor diameter increases from 95 m to 100 m. This behaviour is probably associated with the wind direction sampling in the array efficiency evaluation, as discussed in Section 5.3.4. As a consequence, the array efficiency drops by nearly 1% and the bottom lease decreases 13%.
Since the sensitivity of the investment costs plays an important role in the optimisation, Figure 6-5 presents the breakdown of these costs. Electrical system costs show a break in the trend, caused by the break in the spacing trend, but furthermore the costs increase smoothly. The cost increase of the rotor-nacelle assembly is largest and therefore, uncertainties in the RNA cost model are expected to dominate the uncertainty in the investment costs. The costs of support structure procurement also show a significant increase. The increase is less than that of the RNA costs, so it is expected to have a smaller effect on the uncertainty of the optimisation. Furthermore, the models that

![Figure 6-3 Contributions to LPC as a function of rotor diameter, normalised with the value for the reference RNA](image)

![Figure 6-4 Spacing as a function of rotor diameter](image)
underlie the support structure costs are more detailed than that of the RNA model. Therefore, the trend in support structure costs is expected to be more reliable than the trend in RNA costs. The increase in installation costs of the turbines and foundations is large enough to be visible, but much smaller than those previously discussed. Although these costs are based on simple models, the effect of uncertainties in these models on the optimisation is therefore expected to be smaller than that of the RNA model.

All in all the uncertainties in the optimisation of rotor diameter seem to be dominated by the uncertainty in the model for the RNA purchase price. Even for the fairly uncertain model that has been used here, the tool proved to be useful in the optimisation of rotor diameter in this case study. Turbine manufacturers are expected to have more precise models of RNA costs than the ones used here.

6.3.3 Use case 2 - Finding directions for improvements

In this use case several ‘what if’ scenarios are run with the tool. In a ‘what if’ scenario the values of one or more of the RNA properties are changed, without considering how these changes can actually be achieved through design changes. The five scenarios that are tested are:
1. reduction of the maximum thrust by 20%
2. reduction of the maximum thrust by 10% and reduction of the thrust coefficient by 15% for all wind speeds at the cost of a decrease in power of 5% for all wind speeds below rated
3. increase of the mean time between failures for repairs that require lifting equipment by 20%
4. increase of the mean time between failures for failures with easy repairs by 20%
5. increase of the preventive maintenance interval by a factor 2

Table 6-1 shows the resulting change in levelised production costs for these 5 scenarios. The reduction of thrust at the cost of a loss of power doesn’t give a lower LPC, but all other scenarios are beneficial. The largest reduction in LPC is seen for the increase of MTBF for repairs that need lifting equipment and for the increase in the maintenance interval. The effect of doubling the maintenance interval is much larger than that of the increase in mean times between failures. This is because the mean times between failures are increased by only 20%, instead of 100%. This results directly in a much larger reduction of the costs of consumables and downtime during services than the corresponding reductions during repairs. However, it also results in a larger reduction of personnel costs. In scenario 3 and 4 the number of crews remains the same, while it changes from 5 to 3 in scenario 5. The effect of discretisation of the number of crews on the response of LPC to changes in inputs is discussed in Section 5.3.6. The consequence of this discretisation is a limitation in the resolution of the results of scenarios 3 to 5. In this case, the step of 1 crew corresponds with a change of approximately 2% in LPC. Therefore, the reduction in LPC of scenario 5 is the largest, even when the resolution is considered.

How much of the reductions in LPC shown in Table 6-1 can actually be achieved depends on the possibility and costs of obtaining the improvements of the properties of the RNA. Nevertheless, these results indicate that of the five directions of change, the third and fifth are most interesting to pursue first.

**6.3.4 Use case 3 - Establishing a budget for design changes**

In this use case the budget is assessed that would be available to obtain the improvements of the properties of the RNA of the previous use case. Based on the results of the previous use case, the budget is determined for the increase of the preventive maintenance interval by a factor two. The purchase price of the RNA is gradually increased, until the same levelised production cost is obtained as in the reference scenario. The result is a purchase price of approximately 1.81 M€ per RNA.

Table 6-1 LPC for five ‘what if’ scenarios, normalised with the LPC of the reference scenario

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Normalised LPC [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Lower maximum thrust</td>
<td>0.991</td>
</tr>
<tr>
<td>2. Thrust vs power</td>
<td>1.018</td>
</tr>
<tr>
<td>3. MTBF – lifting</td>
<td>0.979</td>
</tr>
<tr>
<td>4. MTBF - Small repairs</td>
<td>0.997</td>
</tr>
<tr>
<td>5. Preventive maintenance</td>
<td>0.947</td>
</tr>
</tbody>
</table>
This implies that for the V80 a budget of 310 k€ per RNA or over 20% of the original costs would be available to double the preventive maintenance interval of the RNA.

6.3.5 Use case 4 - Testing market robustness

In this use case the previous use cases are repeated for different site conditions or wind farm sizes. This indicates how sensitive the optimisation of the RNA is to variation in the type of wind farm in which it will be used. In the controlled experiment the previous use cases have been repeated for two new targeted markets. The definitions of the three markets that will be compared are:

1. the reference market: farm size of 8x10 turbines – Horns Rev site conditions
2. smaller farms: farm size of 6x6 turbines – Horns Rev site conditions
3. worse site: farm size of 8x10 turbines – Worse site conditions

The conditions at the worse site are the same as at Horns Rev, but with all the negative changes to the site data that were used in the sensitivity study as presented in Table 5-10 of Section 5.3.1.

The results of the optimisation of rotor diameter are shown in Figure 6-6. The optimum rotor diameter and associated LPC are again determined with a 2nd order polynomial through the three lowest points. The optimum rotor diameters are 90.7, 92.0 and 104.5 m for the reference, the smaller wind farm and the worse site conditions, respectively. The effect of farm size on the optimum rotor diameter is not so large, but the effectiveness of the optimisation on LPC becomes larger.

For a smaller farm both energy yield and costs reduce. However, the cost reduction is

![Figure 6-6 LPC as a function of rotor diameter for different targeted markets, normalised by the LPC for a rotor diameter of 80 m](image-url)
smaller, because some of the costs do not scale down proportional to the size of the wind farm. Some of these costs also don’t scale significantly with changes in rotor diameter. The consequence is that the smaller wind farm has a higher LPC with costs that are less sensitive to changes in rotor diameter. Therefore, the increase in energy yield becomes more important and the rotor diameter can increase more before the effect of cost increase gains enough importance to dominate the trend in LPC.

For the worse site conditions the energy yield is mainly reduced by the reduction in average wind speed, while many of the cost contributions increase. This increases the LPC and also increases the contribution of costs that are not affected by changes in rotor diameter. Qualitatively, this leads to the same results as for the smaller wind farm, but quantitatively the effects are much larger. The worse site conditions cause a large increase in fixed costs, while the smaller farm size reduces both fixed costs and costs that scale with rotor diameter. The relative proportion of scaling costs is therefore smaller in the case with worse site conditions. Furthermore, the lower average wind speed increases the sensitivity of energy yield to variation of rotor diameter. The probability of operating in partial load conditions becomes larger and only for these conditions is energy yield a function of rotor diameter. In other words, due to the lower average wind speed the levelling off of annual energy yield is less quick than seen in Figure 6-3 for the reference market.

The results of the market robustness study for use case 2 and 3 are summarised in Table 6-2. In worse site conditions the effect of lowering maximum thrust becomes more important, because the contribution of support structure costs becomes relatively more important. The changes in reliability remain equally important for the new market definitions. Most of the downtime and the costs of corrective maintenance scale with the number of failures. Therefore, a change in failure rate results in similar relative change in repair costs and availability for all markets. The change in preventive maintenance needs has nearly the same effect on LPC for the worse site conditions, but has a much smaller effect on LPC for the smaller wind farm. To explain this difference, the number of crews is also shown in Table 6-2. For the smaller wind farm the number of crews doesn’t change when the preventive maintenance interval doubles. The resolution of LPC corresponding to a change of 1 crew is approximately 4% in this case, because all costs are much lower than in the reference market. The resolution for the worse site condition is about 2%, just as for the reference market. The apparent variation of effectiveness of doubling the preventive maintenance interval is therefore possibly mainly caused by the resolution of the response. Thus, the discretisation of the number of crews does have an impact on the utility of the tool, as anticipated in Section 5.3.6.

Conclusions about utility of the tool

The examples of using the tool demonstrate that it is indeed possible to further optimise rotor-nacelle assemblies, with clear reductions of levelised production costs. Use case 1 shows reductions of LPC in the order of magnitude of 2%, while use case 4 shows possibly much larger reductions for situations that differ more from common markets. This indicates both the utility of the tool and the less than optimum result of the current way of collaboration. However, it is noted that the results for power density optimisation achieved with the tool are currently also visible in trends for actual RNA designs.
Use case 2 shows that the potential of reduction of LPC by different means differs significantly enough to use the tool to point out interesting directions for design changes. The maximum potential reductions in LPC are up to 5%, so significant enough to merit further analysis of design changes. Use case 3 demonstrates that the budget for such design changes can easily be determined and that these are up to 20% of the original costs of the RNA. Again, such budgets merit further analysis of design changes and thus demonstrate the utility of the tool.

The use cases also reveal a little of the effect of accuracy of the tool on its utility. The accuracy appears to be good enough for rotor diameter optimisation, when compared to current uncertainties in the design of the RNA. The trends in the results are clearly visible and larger than a preliminary estimate of the inaccuracies. The effect that sampling of wind directions has on the optimisation of spacing is visibly when using the tool, but it seems to hardly affect the conclusions. The discretisation of the number of crews has a significant negative effect on the evaluation of improvements of maintainability and reliability. An even larger negative effect is expected when the tool would be used to actually optimise these aspects.

### 6.4 Case studies: Tests with wind turbine designers

#### 6.4.1 Introduction and overview

In the case studies the tool was tested by wind turbine designers. The participants spent time working with the tool, after which they filled out a questionnaire to express their experience and opinion. The activities that the participants had to perform were prescribed to ensure that they got a taste of the use cases of Section 4.3.3 and to enable comparison of their feedback. The participants had to choose an offshore wind turbine of their own portfolio as a starting point and they had to select a site and farm size to represent the market for which they wanted to optimise the turbine. The activities were fully described in a test program, which provided background information and

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**Table 6-2 Effect of variation of the targeted market on results of use case 2 and 3; Columns are identified by: 1. Reference market – 2. Farm size 6x6 – 3. Worse site condition**

<table>
<thead>
<tr>
<th>Reference case</th>
<th>Normalised LPC(^a) [-]</th>
<th>Number of crews [-]</th>
<th>Budget for RNA improvement(^b) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Reference case</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Lower maximum thrust</td>
<td>0.991</td>
<td>0.991</td>
<td>0.983</td>
</tr>
<tr>
<td>2. Thrust vs power</td>
<td>1.018</td>
<td>1.021</td>
<td>1.017</td>
</tr>
<tr>
<td>3. MTBF – lifting</td>
<td>0.979</td>
<td>0.978</td>
<td>0.980</td>
</tr>
<tr>
<td>4. MTBF - Small repairs</td>
<td>0.997</td>
<td>0.997</td>
<td>0.997</td>
</tr>
<tr>
<td>5. Preventive maintenance</td>
<td>0.947</td>
<td>0.990</td>
<td>0.951</td>
</tr>
</tbody>
</table>

\(^a\) Normalised by the LPC for a rotor diameter of 80 m

\(^b\) Percentage of the original RNA purchase price
guidelines to perform the use cases of Section 4.3.3. The participants in the test program got the following package:

- the software of the tool
- description of the test program
- a questionnaire
- a concise manual of the tool
- a description of the wind farm concepts and configuration that are implemented
- forms that list the required input parameters

The questionnaire played an important role in the analysis of the experiences. Its set-up and principles for the analysis of the response are therefore elaborated in Sections 6.4.3 and 6.4.4, respectively. At the start of the case study the detailed description of the tool provided in Chapter 4, the appraisal of Chapter 5 and the example runs of Section 6.3 were not yet available. Therefore, the participants had limited information about how the tool works internally and how it performs.

### 6.4.2 Targeted participants

Pertaining to the subject of defining a target group for the participants in the test program, University Library Loughborough University uses the following terms in the context of a survey:

- population – all the members of the group you are interested in
- sample – the subset of the population selected to receive the questionnaire
- respondents – the subset of the sample that actually completes and returns the questionnaire

Using this terminology, the population consists of all offshore wind turbine designers. In particular, designers that are involved in establishing values for parameters that outline the turbine are targeted with the prototype. Typically, these designers work on the interface between marketing and engineering. This population can be found in wind turbine manufacturing and consulting companies, with the majority in the first. The wind turbine manufacturing companies can be further categorised in companies that have delivered turbines for offshore wind farms, companies that offer wind turbines for offshore application, companies that are testing prototypes and starting up production and companies that aspire to deliver offshore wind turbines in the future.

The sample should be representative of the population. Turbine manufacturers that develop offshore wind turbines are known from previously installed wind farms, articles, listed manufacturers, presentations, personal contact etc. Since the development of offshore wind turbines requires large investments and the market for offshore wind turbines is limited in extent, the number of offshore turbine developers can be counted on a few hands. A sample of 4 to 8 companies is therefore considered appropriate, as long as it covers the range of different types of companies. The size of the sample is also kept small to limit the amount of effort required by the industry. The main selection criterion for the sample was the desire to make it representative, but furthermore the preferences are based on practical reasons: offices close by, familiarity with people in the company, earlier cooperation etc. The sample doesn’t represent a quality judgment
of the selected or ignored companies. Table 6-3 shows the categories of the population and the sample. The respondents of the sample are given in Section 6.4.5.

6.4.3 Set-up of the questionnaire

Approach
To get feedback from the test panel about their experience with the tool, a questionnaire has been used. To test specific hypotheses that have previously been generated, a formal questionnaire is more suitable than an interview with open-ended questions\textsuperscript{71}. A formal questionnaire consists of a list of ordered questions with a prescribed response format. This helps to compare feedback from different persons, because it forces them to address the same qualities of the tool. Even though the number of participants in the test will be small, a formal questionnaire enables some extent of statistical analysis. This section provides the rationale for the set-up of the questionnaire and an overview of its content.

The set-up of the questionnaire has a weak methodological basis. To quote Crawford\textsuperscript{71}: “Unfortunately, questionnaire design has no theoretical base to guide the marketing researcher in developing a flawless questionnaire. All the researcher has to guide him/her is a lengthy list of do’s and don’ts born out of the experience of other researchers past and present. Hence, questionnaire design is more of an art than a science”. Although what is observed in this quote may have changed since 1997, such lists of do’s and don’ts are still abundant. Many of the tips and tricks are confirmed by appearing in different sources. A list of relevant tips is collected from various sources\textsuperscript{16, 44-47, 71, 123, 150, 151, 211, 278}. The tips concern for instance the information that is targeted, how to develop the content and the wording of the questions, how to organise the questionnaire and how to address the right audience. Not all tips are relevant to this project. For instance, in the current test program the design of the questionnaire to get a

Table 6-3 Population and sample for the test with the intended users (2012 status used to categorise companies)

<table>
<thead>
<tr>
<th>Part of the population</th>
<th>Examples of companies</th>
<th>Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Not in sample</td>
<td>Companies shown in most relevant position</td>
</tr>
<tr>
<td>Manufacturers with offshore wind turbines installed</td>
<td>Nordex SE</td>
<td>General Electric Company</td>
</tr>
<tr>
<td></td>
<td>Sinovel Wind Group Co. Ltd.</td>
<td></td>
</tr>
<tr>
<td>Manufacturers that offer offshore wind turbines on a regular basis</td>
<td>Repower Systems SE</td>
<td>Siemens AG</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vestas Wind Systems A/S</td>
</tr>
<tr>
<td>Manufacturers that are starting up production</td>
<td>Alstom</td>
<td>XEMC Darwind BV</td>
</tr>
<tr>
<td></td>
<td>Guodian United Power Technology Company Ltd.</td>
<td></td>
</tr>
<tr>
<td>Companies that aspire delivering offshore wind turbines</td>
<td>Gamesa Corporación Tecnológica, S.A.</td>
<td>2-B Energy B.V.</td>
</tr>
<tr>
<td></td>
<td>Sway AS</td>
<td></td>
</tr>
<tr>
<td>Consultancy companies that support offshore wind turbine design</td>
<td>Aerodyn Energiesysteme GmbH Wind Power Ltd.</td>
<td>GL Garrad Hassan</td>
</tr>
</tbody>
</table>
high response rate is not so relevant. The willingness of the test panel depends much more on the amount of effort that needs to be spent on testing the use cases with the tool than on filling out the questionnaire. Furthermore, recommendations about the use of simple language are not followed strictly, since the targeted respondents are well-educated and have a common vocabulary of technical terms.

In the documentation of the test program and in the introduction to the questionnaire that the participants receive, special attention is given to the confidentiality of the data used by the participants. Since the purpose of the questionnaire is the validation of the design theory, most questions relate to the experience that participant had with the tool. Specific data inputs and outputs are not requested. The formulation of the questions aims to allow the participants to provide honest answers about their experience, without jeopardising their company’s interests or confidentiality. Consequently, details about the contents of the runs made by the participants are not published.

**Requested information and type of questioning**

In accordance with Section 6.1.1 the questionnaire should reveal two types of information: the utility experienced by the participants and imperfections in the instantiation that may reduce the perceived utility. As discussed, the utility is expressed with respect to current design solutions and design methods. Therefore, the questionnaire collects information about these references. The subject of the questionnaire is complex and the number of respondents is small. Therefore, there may be quite some scatter in the responses. For proper interpretation, it is desired to have some insight in how the answers came about. Consequently, some information is collected about how the test program has been carried out and about the background of the participant. Thus, the collection of information is divided into the following four subjects:

- data about how the test was carried out
- respondent’s information
- reference wind turbine and design methods
- experience with the tool

The objective data that is collected comprises of the time spent on learning the tool and on working on the four use cases. Furthermore, it is asked which of the prescribed activities have been completed and whether any additional activities have been undertaken on the participants own initiative.

The respondents’ information that is requested to support interpretation of the result are the job description of the participant and his/her years of experience.

Little is known in advance about the reference wind turbine and design methods of each respondent and this information may be sensitive. Therefore, this information is collected using open questions. This formulation of questions elicits qualitative information\(^\text{278}\) and allows complete freedom of report\(^\text{123}\) while closed questions should only be used when it is clear what the potential responses will be\(^\text{123}\). The questions about the reference turbine enquire about its concepts and dimensions, its status of development and its targeted type of offshore wind farm. Questions about the reference
design methods enquire about the procedures and tools that are currently used in the same design phase.

The questions about the experience with the tool form the core of the questionnaire. These questions address the utility of the tool and the imperfections that may reduce its utility. To be able to get more specific questions, these two elements are further broken down into smaller issues. These issues are, ordered from ‘most relating to utility’ to ‘most relating to imperfections’:

- overall perception of utility
- utility of the formulated use cases
- results obtained with the method relative to other methods
- perception of performance of the tool
- interaction with the tool
- external factors that influence the experience

These issues are translated to questions. To test existing hypotheses, close form questions are more suitable than openly formulated questions. Close form questions are easier to code and analyse and they are more suitable to obtain quantitative information. There are several formats of closed questions, such as multiple-choice, dichotomous questions (having only 2 response categories such as “Yes” or “No”), ranking and scales. To measure someone’s attitude or opinion, rating scales as proposed by Likert can be used. The issues in the previous lists are posed in the questionnaire as Likert items. This means that each issue is translated to one or more statements. The respondent is asked to indicate along a scale to what extent he/she agrees or disagrees with the statement. Because the list above could be incomplete, some open questions are added to provide the opportunity to expand on some issues.

6.4.4 Principles of analysis of the response

The structured format of the Likert items provides the means for quantitative analysis of the answers. The rating scale enables averaging of the responses of the different participants, to achieve a general impression. The answers to the open questions are used to analyse differences between different respondents.

Some of the Likert items relate to the utility that was experienced during the test, while others relate to imperfections. Positive answers about the utility confirm the design theory. However, negative answers about the utility may be caused by imperfections in the tool or they may contradict the theory. Figure 6-7 shows how tendencies in positive and negative response are interpreted. The responses are interpreted as being positive or negative according to the following principles:

- positive – agree with positive statement or disagree with negative statement
- negative – agree with negative statement or disagree with positive statement

6.4.5 Response and analysis

Of the six companies that have been approached five have tested the tool and filled out the questionnaire. In consultation with 2-B Energy it was concluded that the tool and use cases did not match with their design philosophy. The tool and use cases are
developed primarily for parametric optimisation of RNA parameters in a setting with a more-or-less fixed configuration of the offshore wind farm. The philosophy of 2-B Energy is to redesign both the RNA and the wind farm concepts and configuration, to get a better match. The tool is not suitable for this conceptual design variation and the concepts that 2-B Energy selected for the wind farm deviate too much from those implemented in the tool. Vestas didn’t answer the closed questions of the questionnaire, because the respondent didn’t feel the purpose of the tool fitted sufficiently with his normal work. However, this respondent gave extensive feedback in writing.

The respondents have in common that all are engineers and most hold an engineering position. One of the respondents works in the sales department, for onshore applications. The experience of the respondents differs from 10 months to 17 years. Only one of the respondents has work that corresponds closely with the purpose of the tool on a daily basis and one respondent does similar work, but usually for onshore rotor-nacelle assemblies. These respondents both mention the use of cost models in there current approach.

The time spent on working with the tool varies from 4 hours to 41 hours, with an average of 17 hours. Two respondents performed all prescribed use cases, while the others used their own interpretation of the test program. The respondents used different rotor-nacelle assemblies as a starting point.

Figure 6-8 shows the response to the closed questions. The response has been processed as explained in Section 6.4.4. The original, full questions are given in Appendix H. The statements in the figure are reformulated to make them shorter and to ensure that agreement with the statement implies positive feedback. The statements are ordered to correspond with the Likert items as introduced in Section 6.4.3. The statements in the top of the diagram relate primarily to the utility of the tool, while the lower statements relate to whether or not imperfections in the tool or in the test program influenced the perception of utility.

The respondents generally agreed with the overall utility of the tool, which can be considered to be the foremost issue in the validation of the theory. Particularly the first statement was widely acknowledged, with limited variation in the response.
Figure 6-8 also indicates general agreement with the utility of the use cases. However, it is noted that most respondents didn’t actually perform the prescribed use cases during the test. Some respondents indicated this by expressing no opinion about the four statements that explicitly ask about the use cases. Therefore, these results indicate as much that the use cases satisfied some respondents during the test as that some respondents considered this to be a potential way of using the tool.

The third group of statements relate to how well the method works relative to existing approaches. There is large variation in the agreement with these statements between the respondents and the average results don’t prove that the tool improves current practice. The most negative response on these issues was provided by the engineer that works daily with other cost models for RNA design. On the one hand, this response is considered to be the most relevant one, given that this respondent has a good reference to make the judgement. On the other hand, this respondent used the tool only for three hours (plus two hours for learning). The negative response may also indicate that the respondent is more comfortable with the (in-house) tools with which he is familiar. On average, the respondents disagree slightly with the statement that the RNA design is better than without the tool. This would be a threat to confirmation of the validity of the theory, as this is one of the main purposes for which the tool is made. However, two observations oppose such a negative conclusion:
1. Considering the small scope of the test program, quality of the final design is likely to be one of the main criteria for liking or disliking the tool. Disagreement with this statement is therefore apparently in conflict with agreement with the first statement about overall utility. This conflict may be caused by reluctance to acknowledge that current designs can be improved.

2. The largest disagreement comes from a respondent that uses cost models for similar purposes. Such cost models for balance of plant and operation and maintenance represent the effect of external designers and are thus implicitly based on this theory. The similarity between the principles of the tool and those of cost models is recognised by another respondent who disagrees with this statement but adds “No better or worse, just different”.

There is also a large variation in the perception of the performance of the tool. Furthermore, the average confidence in the tool is neither low nor high. However, at the time of testing, information about the models in the tool and about the appraisal was not available. Many respondents mentioned the need of documentation and appraisal as a priority to be addressed. It is expected that confidence in the tool improves with the information provided in Chapters 4 and 5 of this thesis. The lack of this information may have caused a negative effect on the perception of performance of the tool. In turn, this may have led to slightly lower judgement of the utility of the tool, for instance in terms of the quality of the resulting RNA design.

The interaction with the tool was generally considered good. Many recommendations given as feedback concern the interfacing, but within the scope of the test program the interfacing of the prototype was apparently considered to be sufficient. Therefore, this aspect is not expected to influence the perception of utility of the tool in a negative way. However, many respondents were not comfortable with the fact that the tool operates in a field with which they are less familiar. This is an important point of attention. This may be an interfacing problem, but it is also fundamentally related to the purpose of the tool. If this cannot be alleviated by providing more information or by educating the user, it may provide a threshold for trusting and using a tool like this.

Most of the respondents had difficulty in finding the time to perform the test program in full. Several found that this was undesirable when forming an opinion about the tool. This may also have had a negative influence on the evaluation.

In addition to the closed questions, the respondents answered some open questions about there experience with the tool. The recommendations for further development given in these answers are presented in Section 7.2.2.
7 Discussion

7.1 Purpose of the discussion

The quote of Horváth at the beginning of this chapter refers to two major issues associated with design inclusive research. The first is the question how design activities can be included in practical research processes. How this is done in this thesis is discussed in Chapter 2. The second question is how the information coupling can be implemented between the research activities and the design activities. This relation between the general theory and the idiosyncratic knowledge about the developed tool is the subject of this chapter.

In Chapter 3 the principles of a design method are developed. These principles are formulated in abstract terms. The development and appraisal of a concrete implementation of an instrument and a validation of the method with this implementation is described in Chapters 4 to 6. However, this implementation is only a prototype, which requires further development before application in actual design of rotor-nacelle assemblies. The research covers both the abstract and the practical level of the issue at hand, but it is open ended on two sides. On the practical side it leaves the question how to proceed to get an implementation that will be valuable in the design of rotor-nacelle assemblies. On the abstract side the question remains how wide the range of application of the theory can be expected to be. The purpose of the discussion is to shed light on these two aspects. In the description of the approach in Chapter 2, these discussions were referred to as contextualisation and consolidation.

The contextualisation leads to the prospect of further development of the instantiation for the design of rotor-nacelle assemblies. As stated in Section 2.2.3, the contextualisation activity aims to provide insight in which fundamental and practical issues need to be addressed in further developments and which opportunities and threats are foreseen, in order to assess further required effort and chance of success.

The consolidation leads to a generalisation of the findings of the research. Section 2.2.3 states that the purpose of the consolidation activity is to generalise the results to other applications in order to assess the validity of the theory in other contexts. The formulation of the theory in Chapter 3 is very universal, and the consolidation treats
what can be expected about the feasibility of other implementations. This includes a review of existing design knowledge that puts the current theory in perspective. The result of this discussion will be a founded insight in further refinement of the wide purpose and scope of Section 3.3.1.

The two discussions are independent and can be read separately. Section 7.2 treats the contextualisation for rotor-nacelle assembly design and Section 7.3 discusses the consolidation.

7.2 Contextualisation

7.2.1 Considerations about the process to introduce the method

The role of the current prototype and this thesis

As already pointed out in Section 4.1, the prototype is not the real tool, to be used in a commercial application. The distinction between a prototype and operational software is often blurred. Indeed, it was noticed during almost all demonstrations and conversations about the tool that the prototype was considered too much as the real thing or at least its nearly mature predecessor. Many questions addressed possible improvements that would be desirable for its final application, but that were unnecessary for the tests. However, the blur in the distinction also has its advantage. Throwaway prototypes may become evolutionary prototypes, eventually leading to operational software. Thus, the prototype of the wind farm design emulation software may be the start of further development.

Even when future developments do not build on the current software, a throwaway prototype increases the initial value of the first real system. Throwaway prototyping is often used as a method to determine and order groups of activities at the highest level of a software development. Davis et al. similarly notice that “The [throwaway prototyping] approach is to construct a […] partial implementation of the system prior to (or during) the requirements stage”. Tate is more explicit and notes that “The knowledge sought [by prototyping] may relate to clarification of requirements, feasibility, user acceptance, marketability, system behaviour, or critical performance factors”. The experience of the participants in the test and their feedback contribute to this type of knowledge. Even though many of these factors are not explicitly investigated, a general impression rises from the experience of implementing the tool, discussing it with potential users and performing various tests. The main findings are documented in this thesis. Particularly, Section 7.2.2 provides a preliminary overview of suggested improvements.

Besides the documented experience with the development and use of the tool, the thesis provides extensive information about the content of the tool. This information is intended to be comprehensive enough to re-program the models. Several choices concerning the software development are made that could be different for operational software. For instance, the choice of programming language and environment is driven by the requirements of prototype development by a non-expert programmer. These choices can be revisited, by re-assessment of the support of the choices in Section 4.1.
Where to continue the development

The prototype may be further developed in its current setting of the academic environment. However, when the purpose of the tool shifts from research model to operational software many requirements that were irrelevant for the prototype will emerge. To deal with these requirements demands a substantial effort that won’t always contribute to the goal of advancing knowledge. Such operationalisation of academic software is possible when users accept relaxation in requirements, when the advance of knowledge from further development merits the effort or when the extra effort is considered to be a good investment in valorisation of academic knowledge. This approach appears to work well in the earlier stage of a development, but often commercial development is eventually taken over by third parties. For instance, OpenFOAM started at Imperial College, London, and is currently owned by ESI group. Another example is Nastran, which is a renewed development of software from various research centres and which is currently available through three commercial parties.

There is experience with different approaches of continued software development regarding RNA design, in particular with software for turbine simulation. FAST is a software tool that is developed by research institute NREL. As an open source code, it is used by researchers but it is not widely spread amongst industrial users. Research institute ECN also developed software for wind turbine simulation, but much more with the intention of commercialisation of the code. Therefore, their program Phatas is used in a few companies. Flex5 is originally developed at DTU, Denmark, but has branched into further in-house versions at Vestas and DONG, amongst others. Similarly, Siemens Wind Power has its own in-house development of BHawC. Probably the most widespread simulation tool is Bladed, developed and licensed by GL Garrad Hassan. GL Garrad Hassan is a consultant in wind energy that can use its knowledge to maintain the software and that has a large network of clients with similar requirements for the wind turbine simulation tool. There are also a few general purpose software developers that have added wind turbine simulation to their structural dynamics solvers, such as LMS Samtech is doing with SAMCEF Wind Turbines.

The previous examples can be classified as:

1. development in a research institute
2. in-house development of a wind turbine manufacturer
3. development and licensing by a wind energy consultant
4. development and licensing by an engineering software house

For these four options for further development and application of the wind farm design emulation tool, the following considerations are given. It is acknowledged that these considerations are somewhat subjective and not supported by evidence. Regarding 1, the chance of successful deployment in the industry is threatened by the scientific priority of research institutes. This combination may result in insufficient willingness or means to spend effort on meeting the clients’ requirements, despite commercial incentives. Development 2 has the advantage that users often have large confidence in in-house tools. Furthermore, experience of the user can directly lead to improvement of the tool. In the case of wind turbine simulation tools this is known to give great advantage, particularly by feedback of prototype measurements to update parametric
models. However, in the case of wind turbine simulation tools the content of the tool matches with the expertise of the wind turbine manufacturer. This is less so for the wind farm design emulation tool. However, many wind turbine manufacturers have departments with relevant expertise, such as the departments dealing with sales of offshore wind turbines or turn key projects. Another disadvantage of in-house development by wind turbine manufacturers is that these have a smaller portfolio of projects from which to draw experience and they cannot share the development costs with others. The consultants of case 3 are in a very good position for development of the wind farm design emulation tool. They can divide development costs over various licensees, they have employees with relevant expertise through their involvement in offshore project development and they have a network of clients and companies that may be willing to share their knowledge. The engineering software houses of case 4 can also divide costs. They may not have the same domain specific expertise and network as the consultants. However, there are companies with experience in software development for engineering design optimisation that they can complement with knowledge about offshore wind energy. These companies can exploit this benefit in the same way as software developers for structural engineering do for wind turbine simulation.

Based on the previous assessment, the wind energy consultants are in the best position for further developments. Engineering software developers with expertise in engineering design optimisation are also in a good position. A joint effort of these two sectors could give an excellent combination of engineering design knowledge, domain specific knowledge and contacts with relevant parties. Project developers and companies with experience in turn key projects can provide knowledge about collaboration paradigms, at least as regards the wind farm design process. Other parties involved in an offshore wind farm, such as cable suppliers and offshore service contractors, can be consulted to provide knowledge about the external design processes. Wind turbine companies should remain involved in the process of continued development, as users of the tool[234]. They can also provide information about RNA design, to properly match the tool with the internal design process.

**Introduction in the industrial environment**

During the execution of this research many people from wind turbine companies have been consulted in more and less formal ways. Particularly, people have been contacted to gain their participation in the validation tests. Usually, initial contact was established with engineers, but this sometimes led to contact with people from sales or marketing. This has resulted in a perception of some hurdles that need to be taken during the introduction of the tool in an industrial environment.

Most noticeable is that the working method that is proposed in this thesis is so new to most people that it requires an effort to create the right mindset. In first instance the tool that emulates offshore wind farm design is often seen as a support for project developers or offshore turbine sales departments. This is the more common application of design optimisation tools, where the tool optimises the artefact that the engineer is designing. However, in this case the external design processes are emulated, rather than the internal design process. Most people don’t have a reference tool or method, with which they can compare this new development. The closest reference would be the use of cost models for offshore wind farms in the requirements phase of the RNA development.
These cost models also provide information about the optimality of the rotor-nacelle assembly in its final system, albeit with far less detail. Indeed, it helps to point out that the tool can be considered to be an elaborate and detailed cost model. The current version of the tool can be characterised as such, but it doesn’t do justice to the potential of the method to provide much more information about system level trade-offs than just the costs. To exploit the full benefit of the method in an industrial environment requires new users to develop an understanding of the way of working by educating the ideas behind it and by experiencing it. The validation case studies are a start of this process.

The novelty of the method leads to a second, but related hurdle. It was difficult to find people that consider the activity that is performed with the tool to be part of their normal work. Consequentially, few people considered to method to solve any of the problems they experience in their daily work. This is surprising, considering the widespread acknowledgement of the importance of cost of energy reduction and design integration for offshore wind energy. Both engineers and people working on the strategic side of developments have been contacted. The general impression obtained from engineers is that they see the benefit of the tool, but that they are not normally involved in performing the trade-offs that are addressed by it. Once the engineers become involved in the design process, key figures such as rated power and rotor diameter are already fixed by the management. Such choices appear to be dominated by people that prepare strategic decisions. However, some of these people responded that they have too little technical background to work with the tool. They may have experience with costs models that perform the same function, but the tool requires insight in RNA design to generate the input data. These data need frequent updating while performing the use cases. The tool should bridge the gap between engineering and portfolio strategy, but at the moment many companies don’t seem to have people working in this position. This gives the impression that working with this method requires a change in organisation. The actual current way of working could not be derived from the responses of the questionnaire, but several people that work on the periphery of this activity confirm to have a similar impression. As for creating the right mindset, the change in the organisation has to start with awareness and understanding of the way of working.

A consequence of the method is that the tool operates in a field with which the users are less familiar. Several reviewers indicated that this made them uncomfortable. This discomfort may partly be removed through more appraisal. For instance, users of pocket calculators don’t need to be experts in mathematics to feel comfortable when using it. They trust the outcome of the calculator, even if they don’t have a reference or intuition to compare the results with. However, further education in the working of the tool and interpretation of the results may be desired.

The previous considerations conclude with the need for education and adaptation of the users. However, the tool is expected to be the most important means of transferring knowledge from this research to industrial practice. As discussed in the previous section, this isn’t necessarily the prototype of this research. The tool is supposed to capture most of the knowledge and thus bring it into the industry without much need for education. A good tool, with intuitive operation, will help the user to perform the proposed use cases and create new ways of using it. It is recommended to let the tool introduce itself as much as possible and thus avoid the need for elaborate prescriptions of new working procedures.
7.2.2 Improvements of the design emulation tool

There is room for improvement of the tool that is created in this project and of the way in which it is used. This section suggests several improvements, focusing on the tool and not on the way it is used. Some improvements of the tool are consequential to the imperfections that are intentionally chosen for the tool in its function as a prototype, but that are considered undesirable for an operational version. For instance, the assessment of fatigue of the support structure was omitted to avoid lengthy computations. Other imperfections appeared during the appraisal and validation of the tool.

The possible improvements of the tool are expected to be numerous, if not endless. In the following, all suggestions done by the reviewers of the tool are mentioned, albeit sometimes not at the original level of detail. Reviewers were asked which improvement they considered to have priority or be absolutely necessary. If one or more of the reviewers deemed an improvement a priority or necessity, this is indicated by the additions ‘(Priority)’ and ‘(Essential)’, respectively, in the lists below. In addition, the improvements needed to alleviate imperfections found in the appraisal and controlled experiment are listed. These are identified by ‘(Test results)’. Finally, some general suggestions of the reviewers and ideas of the author that were not realised in the prototype are mentioned. The improvements are ordered in four categories: confidence in the tool, functionality, performance and interfacing with the user.

Confidence in the tool

Documentation of the models (Essential)
Several reviewers mentioned the necessity of documentation of the models. They also want to know how input parameters are used in the tool. Furthermore, several users don’t feel comfortable with the fact that the tool operates in a field with which they are less familiar. Proper documentation may help to educate the user in this field and alleviate the discomfort. It is noted that the reviewers didn’t have access to the descriptions of the tool that are now available through this thesis. This thesis is expected to be a large step in accommodating the wishes concerning documentation. Nevertheless, a dedicated theory manual would make the information more accessible.

Validation or benchmarking of the tool (Essential)
The reviewers considered validation of the tool essential, for instance by comparison of the results of the tool with actual information of existing offshore wind farms. The word ‘validation’ used here by the reviewers has the same meaning as ‘appraisal’ in this thesis. As for the documentation, the reviewers didn’t have access to the description of the appraisal that is presented in this thesis, which is expected to be a large step in accommodating the wish for validation. Further validation of the tool remains necessary, particularly when the tool is further developed.

Consequence of assumptions
Several assumptions are made in the physical models, the cost models and the design algorithms of the tool. It is desired to know whether these assumptions impact the ranking of different RNA designs. To some extent, this desire is covered by the sensitivity analysis in the appraisal. The sensitivity analysis indicates whether the
ranking of designs is in agreement with expectations. Nevertheless, it has not been demonstrated that the ranking is not changed when assumptions are changed. The effects of changing assumptions in the models should be further assessed.

**Functionality**

**More options for the user (Essential)**

The reviewers would like to have more control on the processes that take place inside the tool. For instance, the user would like to be able to modify values of parameters that are internally defined, such as the interest rate or cost parameters. Another example is the wish to fix some design variables of the wind farm, such as the positions of the turbines. These options enable the user to influence the wind farm design and evaluation. Such options were intentionally shielded from the user, because the user was not considered to have or need the knowledge to influence the wind farm design. However, also in actual collaborative design such ‘what if’ scenarios are used. Giving the user more access to the internal parameters expands the possibilities of the tool with limited effort. However, it is recommended to protect users from unintended influence and from being overwhelmed by the amount of parameters. For instance, it should be easy to revert to default settings and perhaps these options should only be available to users with extra permission. The principle of granting different rights based on the type of expertise of the user has been applied in other knowledge management systems\(^\text{195}\).

**Increase the turbine parameters like rotor speed, torque etc. (Essential)**

During the derivation of the tool it is assessed which RNA parameters may influence the wind farm design. Because simple models are used for the prototype, the influence of some parameters has been neglected. For instance, rotor speed has an effect on the frequencies of excitation of the support structure. In turn, this may affect the dynamic response, the fatigue and finally the design of the support structure\(^\text{287}\). Further assessment of RNA parameters whose influence has been neglected is desired, in combination with improvements of the models that are discussed in the sub section ‘Performance’ below.

**Automation of routine user actions**

Several actions of the user are expected to be performed routinely. For instance, the user will perform parameter variations and post-process the results to determine gradients of costs and to trace the dominant factors that affect the LPC. In use case 3 of the test program the user determines the budget that would be available for an improvement of the RNA by a tedious iteration of the RNA purchase price. Such routine actions and post-processing could be pre-programmed.

**Automation of input generation for a generic RNA**

Several input parameters of the RNA can be estimated using models. This is done in the controlled experiment of Section 6.3, where scaling rules are applied to assess the changes in RNA parameters when the rotor diameter changes. There are also more extensive models to automate the generation of RNA inputs, such as numerical design optimisation\(^\text{26}\). This is intentionally not a part of the design theory of this thesis, since it
is considered to be the responsibility of the user. Nevertheless, enabling the tool to integrate or couple with such models will accelerate the overall optimisation process.

**Increasing the scope of application**

The previous suggestions extend the functionality of the tool, but keep the purpose of the tool the same. The potential of increasing the scope of the tool could also be explored. For instance, the tool might be extended to increase the support of concept and configuration design or to increase the support of detailed design. The expectations about possible increase in scope are not discussed here, because a general discussion of the potential scope of the theory follows in Section 7.3.

**Performance**

**Essential improvements**

None of the reviewers suggested an improvement of performance that they considered to be a priority or necessity. This may imply that they consider the performance to be up to par, despite that performance didn’t rank particularly high in the review. However, it is also noted that the reviewers didn’t have the model descriptions and appraisal results. This means that they had limited information to assess the performance. Most recommendations for improvement given below follow from the results of the appraisal.

**Remove discretisation of the number of crews (Test results)**

The discretisation of the number of crews causes discontinuity in the response of LPC to changes in input parameters. In the controlled experiment this was found to lead to the risk of incorrect optimisation or incorrect conclusions. The possibility to avoid this problem should be explored.

**Include assessment of fatigue of support structure (Test results)**

The appraisal indicates that the omission of fatigue analysis leads to masses of the support structure that are generally too low. Furthermore, the simplified model of fatigue is not expected to perform equally well for a range of different rotor-nacelle assemblies and environmental conditions. It is recommended to extend the model with an assessment of the fatigue limit state. Besides changing the contribution of support structure costs to the LPC, this will reveal the effect of designing the RNA for lower load variations, e.g. through improvements in control algorithms.

**Reassess the evaluation of operation and maintenance (Test results)**

The appraisal yielded unexpectedly high availability and high maintenance costs. However, insufficient reference data was found to further assess whether the results are unrealistic and, if so, what caused the error. The appraisal provides confidence in the design algorithm for operation and maintenance, so further analysis should focus on the evaluation models and parameter values.

**Combat erratic response of spacing optimisation (Test results)**

The response of spacing was found to be erratic. Some ratios between row and column spacing appear to be avoided, due to alignment of the turbines along the sampled wind directions. Further analysis should reveal whether the magnitude of the erratic response
is significant enough to negatively affect the use of the tool. If so, it should be assessed whether this can be combated by improving the array assessment algorithm or whether the optimisation algorithm should also be adapted.

**Other advances in physical and cost models and design algorithms**

The previous items discussed improvement of models for which the appraisal identified a deficiency. However, many other models can also be improved. Further assessment of the performance of the tool may identify these models. However, the necessity of improving models also depends on the purpose of the user. For example, a user that focuses on optimising the reliability of the RNA may not need improvement of the load assessment models. Improving models will usually entail a trade-off between accuracy and computation time. To reduce development and appraisal time, existing tools may be coupled to the emulation tool. For instance, a wind turbine simulation tool may perform the fatigue assessment. The improvement of models and design algorithms may have far reaching consequences. Three examples of possible improvements are discussed, to show some larger consequences of improvements.

1. When fatigue assessment for the support structure is implemented, this constraint could be expanded with the effect of wakes on the turbulence in the farm. This would violate the current separation of constraints between the layout optimisation and the support structure optimisation. As a consequence, the separation of these two optimisations in the implementation would no longer be acceptable.

2. The tool currently estimates the lowest LPC for one configuration. Different concepts and configurations could be added to the tool, to optimise the wind farm for a wider range of conditions. For instance, the addition of a jacket structure would increase the range of application to larger water depths. In some cases, a different concept can be implemented as a replacement of an existing concept, without consequences for other parts of the program. This is likely to be the case for the example of the jacket structure. However, a conceptual change may also have a more widespread effect. For instance, the jacket structure could actually have different accessibility than a monopile, requiring modification of the evaluation of availability. The guarantee of consistency is more complicated when working with changeable configurations.

3. Currently, no constraints are applied on the area used by the wind farm. Neither does the tool consider other site specific aspects, such as bathymetry and pipelines inside the area. Such restrictions may be added to the tool. However, this would require guidelines for the user to avoid that the RNA is unintentionally optimised for a very specific situation.

**Interfacing with the user**

**Definition of all parameters (Essential)**

Several reviewers identified the need to define all input and output parameters. Besides the information in this thesis, it would be helpful to have a list of definitions or additional information for the input and output screens.
Visualisation of input and output (Priority)

It will be helpful to use graphical information in the user interface. Graphs of for instance the power curve and thrust curve may help to avoid making errors in the input. Graphical representation of the design results will help to quickly judge the results. Graphs of output will especially be helpful when the tool is expanded with more routine actions and post-processing, for instance for sensitivity studies.

Other improvement in user interface (Priority)

Many other improvements of the user interface are desirable. For instance the ability to exchange input and output data with other programs is recommended. Also, the possibilities to perform file management are desired to be extended.

7.2.3 Spin-off applications of the tool

Several participants in the tests and other people with which the tool has been discussed are interested in using modules of the tool. This could be as an addition to other cost modelling tools or as a benchmark for such tools.

The tool is developed for use in the wind turbine design process. However, since the tool designs an offshore wind farm, it may also be of use to people involved in project development. As mentioned before, the association of the tool with project development has actually been made by many of the persons with which the tool has been discussed. The most comparable application is the use of the tool to select the RNA for a project. However, the tool may also provide a preliminary design solution, information about economic feasibility of a project or help with selecting a site. The use of the tool to support wind farm development will raise different requirements. For instance, for wind turbine optimisation the optimality of the wind farm and the absolute value of LPC are not of primary importance, as long as it provides proper response to changes in the RNA. Also, the use of a single configuration of the wind farm is probably often sufficient for turbine optimisation. However, such relaxations may not be desirable for wind farm developers. Nevertheless, the reactions of people involved in project development indicated sufficient interest to further explore this possible use as a spin-off.

Since the tool covers the entire range of aspects from physics, through design to cost of energy, it may be helpful in the assessment of importance of different aspects. For instance, the tool might be extended to assess the effect of uncertainties in physical models or input data on cost of energy. Similarly, it may be extended to assess the effect of innovations on the cost of energy. Such capabilities would help prioritising research and innovation and may lead to better insights in the risks of offshore wind energy. Notwithstanding this potential, the extensions needed to achieve these goals are not considered trivial.

7.3 Consolidation

7.3.1 General considerations

The emulation of collaborative design formalises the thought processes of engineers in algorithms. Capturing creative design in algorithms is the field of knowledge based
engineering or in a wider sense of artificial intelligence (AI). The strengths and weaknesses of artificial intelligence appear to be correlated to the dichotomy of design paradigms of Dorst\textsuperscript{94}, who characterises design as rational problem solving or as reflective practice. Rational problem solving is a strength of AI, while reflective practice can be considered its weakness. Dorst notes that early analytical paradigms of design tried to be rationalised and automated, but that the theoretical models from those times were rightly criticised for being overly rational, weak in the description of the design processes, and, worst of all, impractical. More recent work is based on the philosophy of cooperation between artificial intelligence and natural intelligence, instead of the classical expert systems approach of automated design\textsuperscript{41, 64, 181}. The use of artificial intelligence for emulation in the current theory does not have the opportunity to combine the strengths of AI with that of human designers. The user is not expected to interact with the emulation of the external design processes, because it is not expected that he or she has the necessary expertise. In the implementation for rotor-nacelle assembly design, the user is not expected to contribute to the design of for instance the electrical system or the support structure. The tool has complete responsibility to contain the knowledge of offshore wind farm design and to bring it into the wind turbine manufacturer’s design process. This difference between emulation in the current theory and the use of artificial intelligence for other design support needs to be considered when judging the feasibility of emulation.

In most design applications artificial intelligence contributes directly to specification of the artefact that is being designed. For instance it may provide suggestions for concepts, configurations or dimensions. Any imperfection in the models that are used leads directly to reduction in quality of these suggestions. In the current application AI provides design suggestions for the external artefacts. These suggestions have an indirect effect on the quality of the artefact that is being designed. The tool that is developed in this thesis suggests values for design variables of various components of an offshore wind farm, such as the support structure. This influences the quality of the rotor-nacelle assembly through the levelised production costs that are based on these design variables, because the LPC is used as an assessment parameter for the RNA. The emulation does not directly provide design solutions for the internally designed artefact. When parameters in the internal design process are varied, many imperfections in the response of the emulation are correlated. Therefore, much of the imperfection cancels out in a comparative study of design options. This reduces the need of absolute correctness of the emulation, as long as it deals properly with variation.

In summary, the need to model every relevant activity of the external design processes in the tool challenges the feasibility of the emulation. However, the demands on the quality of the results are lower than in other applications of artificial design intelligence.

### 7.3.2 Views on design

During the development of the emulation tool in this thesis the basic design cycle proposed by Roozenburg and Eekels\textsuperscript{241} is used to interpret the waterfall design paradigm in the field of engineering design (see Section 4.3.2). The basic design cycle represents a fundamental view on design that describes it as an iterative process. In this view design solutions are synthesised, their expected properties and value are determined and these are evaluated against established criteria. When the theory of this
thesis is applied, these criteria need to be defined for the entire system and not for the sub-system of the internal design process. The emulation is used to evaluate the sub-system by first emulating the design of other sub-systems and consecutively determining system properties and values. As such, the emulation is an expansion of the evaluation step in the basic design cycle. The inputs of the emulation can be the sub-system specifications, just as they would otherwise be used in the evaluation. When design is viewed in this way, the only changes to the internal design process are the use of system level criteria and the iterative evaluation of sub-system design solutions with the emulation tool. The only collaboration that is exploited in this approach is the system-level evaluation, which only has an indirect effect on the synthesis of solutions. This use of the theory is close to the practices in non-collaborative development, but it doesn’t fully use the potential of collaboration emulation. Because the expository instantiation is based on this view, it only demonstrates the feasibility of one of the more straightforward implementations, but it doesn’t show the extent of what can be achieved with the emulation of collaboration.

A second, possibly complementary, view considers design as dynamic mapping between different domains. The word domain in this context refers to conceptually different types of information, and examples of domains that are used are functional, behavioural, structural, physical and mathematical domains. This model of design is relevant, as function-behaviour-structure mapping is one of the cornerstones of systems engineering. Choosing domain mapping as the framing view of design for the proposed method has several consequences. The internal design process needs to adopt the same approach, which may request large adjustments or extensions. For instance, in the case of RNA design the functional domain is usually not explicitly charted, as far as known to the author. The mapping from function to structure is often done intuitively, based on tacit knowledge of the required functions. In this view the descriptions of the design problem and solution in the different domains become elements of the interfaces with the emulation tool. Since domain mapping is a creative process, emulation of the external design and collaboration engineering processes requires strong models of cognitive processes. This may be on the limit of current capabilities of artificial intelligence. The pay-offs would be that this view enables emulation of stronger collaboration in various domains, thus supporting synthesis of solutions more directly.

The third view that is considered is C-K theory. The discussion of the basic design cycle and domain mapping models above assumes a process that steps between the design problem description and a description of the structure of the solution. C-K theory poses that designers also work with assumed unknown objects that have certain properties. This enables designers to work with solutions of which the structure is partly unknown. An essential characteristic of such solutions is that the logical status of the validity of their existence is initially undecided. For unknown parts of the solution the interface parameters that present the structure of the solution are replaced by the assumed properties. When these properties sufficiently represent the sub-system, the emulation of external design and collaboration engineering processes in this paradigm is similar to that in the view of the basic design cycle. The second and third use case applied in the validation of Chapter 6 implement this view on design for the internal design process. In these use cases the rotor-nacelle assembly is assumed to have certain properties, without actually specifying how these can be achieved. The use of properties as interface
parameters enables the internal design process to work with unknown solutions as hypothetical inputs for the emulation. This allows assessing the consequence for the system if a property of the internally designed subsystem is changed, rather than if its structure is changed as in the basic design cycle approach. Using partly unknown structures for the externally designed subsystem in the emulated design simplifies its implementation, but reduces confidence in the results because of the undecided logical status. Examples of this type of implementation are high level cost models, since these provide a cost evaluation of the externally designed sub systems, without specifying their structure. This view on design thus increases flexibility of the use of the emulation and may simplify its implementation. However, this comes at the cost of reduced confidence in the results of the emulation.

The explicit selection of a view on design is not necessarily crucial to the success of an instantiation of the theory. As identified above, C-K theory has been applied in both the creation of the tool and its use, without explicitly addressing this theory. As observed by Taylor266 “The wide variety of models that have been published and the fact that no one model has been universally adopted must be indicative of a fundamental difficulty inherent in the definition or description of design. It also shows that a formal model of the process is not a prerequisite for successful design, since it is practised daily with varying degrees of success.”.

7.3.3 Classes of design
In this discussion taxonomies described by Dym97, Miles and Moore204 and Otto and Wood231 are used, each using three classes of design. The first class of creative design, inventions or original design is characterised by these authors by original thought, high difficulty, incomplete knowledge and requiring large effort. In the second class of variant design, innovation or adaptive design the difficulties of creative design are moderated by better fundamental physical knowledge, particularly from similar products in other contexts. This enables better decomposition of the problem, but there is still lack of knowledge about how to apply the fundamental knowledge in order to obtain optimal solutions. The third class of routine design, design from previously known sets of alternatives or design of existing products in a marginally changed context can rely on good fundamental physical knowledge and good knowledge about the process to effectively apply the knowledge to generate solutions. The emulated offshore wind farm design of the implementation can be characterised as routine design. This doesn’t mean that the tool can only be used for routine design of rotor-nacelle assemblies, nor does it imply that all offshore wind farm design is routine. However, the success of the current implementation can be associated with the choice of modelling a routine design process. According to Miles and Moore, only the third class of design was beginning to benefit from design systems at the time (1994), while he calls claims of capabilities of original though of computers tenuous. Others also noted that in the research of design informatics, the paradigm of automated techniques based on artificial intelligence shifted to knowledge intensive systems without built-in problem solving capabilities145 and that knowledge-based systems are best suited to routine design problems21. This corresponds well with the general consideration about artificial intelligence given in Section 7.3.1. The association of the design classes with the availability of physical and process knowledge implies that feasibility of emulation increases with “routineness” of the design. The probability of success of the proposed
method is therefore larger when the external design processes can be modelled as routine design.

Several authors emphasise the evolutionary nature of design, where existing products provide the basis for modifications. Development of computer-aided design (CAD) methods can benefit from this model of design\textsuperscript{182}. According to Vajna \textit{et al.}\textsuperscript{281} the evolutionary nature applies both to development of new products and change of an existing product. Keller \textit{et al.}\textsuperscript{172} show how the ability to predict change propagation can guide designers through conceptual design allowing them to analyse design alternatives and foresee potential problems arising from the product architecture. This implies that routine design of a reference architecture of the externally designed sub systems may nevertheless be useful for a less routine internal design process. In the expository instantiation the rotor-nacelle assembly design can be considered to be routine design for a state-of-the-art horizontal axis turbine. However, with little modification the same emulation could be useful in the optimisation of vertical axis turbines, which are not routinely designed.

Henderson and Clark\textsuperscript{137} propose a refinement of the class ‘innovation’ that is helpful in the current context of system innovation. They separate change of core concepts from change of linkages between core concepts. With current knowledge, the method appears most suitable when the architecture remains unchanged. It might be used in incremental innovation, where the core concepts are reinforced, and in modular innovation, where the core concept of the internally designed sub system is overturned. Implementation of emulation of design where the system architecture changes during the design process is much harder. This difficulty was also encountered during the validation. One of the wind turbine companies has a design approach in which the wind farm architecture is evolving and this approach couldn’t be supported with the developed tool.

### 7.3.4 Design phases

Many papers provide a high level division of the design process in phases\textsuperscript{72, 148, 176, 227, 277, 313}. Most divisions share phases for requirements analysis and functional specification. In the implementation for offshore wind energy these phases were not emulated, but the results of these phases were fixed in advance. For instance, the levelised production costs were selected as the objective function during the development of the tool. These phases require such complex cognitive processes and interaction with clients that it is assumed that current design knowledge is insufficient to fully emulate these phases. These phases are followed by the generation and evaluation of solutions, which will be regarded in more detail.

Several authors propose or identify configuration design\textsuperscript{21, 62, 308}, architecture design\textsuperscript{231, 277} or system level design\textsuperscript{248, 277} as one of the early solution generation phases. This phase is typically concerned with selection of core concepts of the components, interconnecting the components and selection of main parameters of the components. Concept selection, configuration definition and dimensioning often reappear in subsystem design activities, following a sequence of continuous increase of level of detail\textsuperscript{72, 148, 176, 227, 277, 313}. The feasibility of emulation of these design activities depends highly on the strength of the knowledge to externalise cognitive processes and on the computational capacity to deal with the increasing extent of computations with
increasing detail. Concept selection is a more subjective activity, and as discussed in Section 7.3.1 this involves cognitive processes that are more difficult to externalise. Other authors also identify issues that hamper emulation of concept and configuration design, such as an apparent lack of knowledge and basic principles to formalize and evaluate conceptual design decisions and a lack of heuristic knowledge. Dimensioning is a more objective, rational activity that can easier be reproduced with artificial intelligence. The knowledge about formalising configuration and topology design is in between that of the two other activities. The implementation for offshore wind energy represents the most feasible option. It only performs dimensioning of a fixed configuration and the design algorithms and models have a level of detail corresponding with a preliminary design phase. There is sufficient knowledge to model this activity and it is less computationally intensive than detailed design.

Despite the difficulties, current knowledge of design can certainly contribute to more powerful emulations than those of the expository instantiation. Section 7.2.2 also proposes extension of the tool with more conceptual variation and more detailed models, albeit with notes of care. Although automatic generation of design solutions from the requirements appears to be unreachable at the moment, there seem to be opportunities for approaches that start from several predefined concepts and configurations. This is supported by the success of case-based reasoning approaches and the observation of Cross that solution-focused strategies are perhaps the best way of tackling design problems. However, Ulrich and Eppinger identify the following potential dysfunctions of fixing a limited number of design solutions: Consideration of only a few alternatives, failure to consider concepts of related and unrelated products of others, ineffective integration of promising partial solutions and failure to consider entire categories of solutions. Nevertheless, as discussed in Section 7.3.1, imperfections in the emulation have only indirect effects on the design quality. Therefore, the consequences of these dysfunctions for the internal design are less than when only a limited number of design solutions are selected for the internally designed sub system.

A restriction of application of the method to dimensioning would be a large disadvantage for the theory. Many authors emphasise the importance of decisions made in the conceptual design phase, since they dominate the eventual properties and performance of the final system. Rehman and Yan state that during concept selection consequences on its life-cycle, its users and its operational environment are generally unknown or neglected. Chong et al. observe that the conceptualization phase is the least supported by computer-aided design (CAD) tools, which can be inefficient if not treacherous. This shows a need for an emulation tool in the conceptual design phase, particularly since the interactions between the internally and externally designed sub systems play an important role in conceptual design. The more detailed the design of the internally designed sub system becomes, the less the emulation tool can contribute, because the importance of interactions reduces. Ulrich and Eppinger remark that concept selection can be applied in a hierarchical way, e.g. by making an early decision about two main solutions and only pursuing concepts for one of these two. Translated to the current method, this can be associated with fixing the main solution for the externally designed sub systems, while pursuing conceptual alternatives for the internally designed sub system. This suggests that while selection of main parameters for the externally designed components is the most feasible option for emulation, this still enables concept selection, configuration design and dimensioning for the internally designed sub system.
designed components. This observation is in line with the previous discussion of the view of C-K theory on design (see Section 7.3.2). The tool is able to work with undefined details of the internal sub system and working with undefined details of a solution is typical in the conceptual and preliminary design phase. However, a point of attention is the possibility of inconsistencies. When configurations or core concepts are changed, interfaces between internally and externally designed components may not be compatible or the configuration may no longer match the functional decomposition of the system. For instance, the tool may be used to optimise a stall controlled wind turbine, but there is no warning that a farm with this type of turbine may not have the grid fault ride through capabilities that are required. Nevertheless, open-minded use is encouraged, since Fricke\textsuperscript{115} observed that successful designers use a flexible methodical approach.

7.3.5 Type of system development

The theory divides the design in an internal process and external processes. This means that the responsibilities in the system development need to be divided. In the expository instantiation the internal process is responsible for the design of the rotor-nacelle assembly and its maintenance procedures. The external processes design all other components and procedures for an offshore wind farm. This division of responsibilities is easiest when the system is modular. Inversely, when there is lack of collaboration between different contributors of a system, that system is likely going to be modular, with different components being designed in different companies. The level of modularity is determined by the mapping between physical chunks and functions, which is bijective for the most modular architecture. In integral architectures functions may be performed by groups of components and modification to one particular component or feature may require extensive redesign of the product\textsuperscript{277}. In particular, this redesign may entail remapping the functional domain to the physical domain. Since artificial intelligence in design applications is still a challenge for devices with highly connected components and integrated functionality\textsuperscript{21}, implementations of the theory are currently most feasible for systems with a high level of modularity of at least two modules. This is hardly a restriction, since modularity is expected in developments with limited collaboration. The external system may be composed of multiple modules that require multidisciplinary design. Objectifying statements and arguments is important in multidisciplinary teams\textsuperscript{94}, which matches the need of externalising knowledge to emulate the design.

Although modularity is a prerequisite for feasibility, implementation of the theory is not expected to have benefits for all modular systems. The wind farm design emulation tool showed utility because changes in RNA design had a significant effect on system-level trade-offs through changes in the external sub systems. The method is most needed for the design of those sub systems that have large coupling with other sub systems. In the case of RNA design, the effect of coupling is mostly one way. The design of the RNA affects the design of other components and procedures, but the RNA design is hardly affect by the wind farm design. This facilitated the implementation and use of the tool, for the only feedback that was used from the tool was the evaluation of the objective function. When constraints in the internal design process depend significantly on design variables of the tool, the internal and external design cannot be separated like this. Various approaches of multidisciplinary design optimisation can be applied to create an
Emulation is more feasible if the interconnections between components are fixed. This condition is best met for systems with a mature basic product technology, since that is an indicator of a more fixed architecture during the system-level design phase. This relates to the identification of routine design as a suitable class of design for implementation of the theory (see Section 7.3.3). Offshore wind energy systems have sufficient maturity to identify possibilities for routine design that were implemented in the expository instantiation. However, it is also young enough to expect a role of innovations and inventions that cannot be emulated. Therefore, emulation tools for less mature developments will need frequent updating with new architectures, such as is also suggested in the improvements of the wind farm design tool in Section 7.2.2.

Following the point of departure, the primary characteristic of design processes that have a need of this method is limited collaboration. Lack of collaboration is most evident in open systems, whose constituents change throughout their lifetimes (definition taken from Suh). Additions and replacements to such systems are not fully designed upfront due to spread over time of the actions and the consequential evolutionary development. The socio-technical development of large infrastructures analysed by Bots falls in this category. The development of offshore wind farms in the context of electricity supply can be considered to be such large infrastructure. In design of close systems, lack of collaboration can exist in product development with sub-suppliers and main-suppliers, but possibly also in collaborative design during periods of more autonomous operation of the design teams. The need of emulation to provide information about external design is largest in open-system design, because there are less or less-effective alternative means. However, the more open-endedness of such system in both scope and time makes it more difficult to collect the knowledge pertaining to the external design processes and to define a collaborative design paradigm for the emulation. Feasibility of emulation is larger for the more contained and better defined design problems of closed systems.

7.3.6 Incompleteness of the theory

According to Dorst, design methods are formed by combining models of the designer, the design task and the design process. The development process provides the basis for the state-space model, yet the designer, design task and internal design process are not further detailed in the theory. Consequentially, other models are needed to make the necessary refinements during implementation, such as Chapter 4 reports for the RNA design. The missing link is explicit guidance in the selection of these models. The theory also does not provide explicit guidance for the reduction of scope, nor for dealing with the imperfections that result from the choices that are made. Without additional theories and propositions to close this gap, implementation puts high demands on the implementers and leaves much uncertainty about its success. The same level of success that has been achieved with the current prototype might not be reached if another implementation is made, based on the same theory. However, Horváth observes that it is a general issue of design research that alternative design solutions that follow the
same theory may have different impact on the evaluation of the theory. In addition, Dorst\textsuperscript{94} notes that it is a common characteristic of methods in the problem solving paradigm to be more abstract, more general and independent of the designer and the design task.

According to Cross\textsuperscript{72}, a design strategy should provide you with two things: a framework of intended actions within which to operate and a management control function enabling you to adapt your actions as you learn more about the problem and its responses to your actions. Yadav \textit{et al.}\textsuperscript{310} identify activity structuring as one of the three key areas in product development research and Efatmaneshnik and Reidsema\textsuperscript{103} identify organisational knowledge as one of the three types of knowledge relevant to design planning. The current theory lacks such strategic guidance to fit the method in the larger framework of a methodology. This lack was also observed during the case study, which led to the conclusion that the current way of working in companies often doesn’t match with the proposed method.

Bots\textsuperscript{40} identifies two difficulties in the development of large socio-technical systems. One difficulty is that the environment may change during the long development of the system. The other difficulty is that many design processes are interlaced in the larger development process. The current theory only addresses the second difficulty and then possibly only partly. The theory does not provide guidance when the network of design processes is too large to emulate a corresponding collaborative design process or when the development time implies continued learning and developments of the externally designed sub systems. In the expository instantiation the network of design processes could be limited by reducing the essential extent of offshore wind energy to markets that can be represented by one wind farm.

The inevitable reduction of scope of the emulation tool generates constraints on its application. Hard-coding results of early design processes is expected to fix system architecture, reference concepts for the externally designed sub systems and interconnections. Although the purpose of the method is to minimise the difference with collaborative design, the rigidity of practical implementations may perpetuate the status quo of the non-collaborative system from which it is derived. Since non-collaborative systems tend to be more modular, the method is not expected to lead to more integral systems. This is a disadvantage, because integral systems have been associated with high performance\textsuperscript{277}, low costs\textsuperscript{231} and resource effectiveness\textsuperscript{59}. However, it is uncertain whether this limitation of the method is the bottleneck for change, as the status quo may just as well be maintained when it is not used. As observed by Eckert \textit{et al.}\textsuperscript{100} "change processes become problematic when change to one system propagates to other systems, because the tolerance margins of individual parameters are exceeded". This indicates that the problem of changing this type of system is universal.
8 Conclusions

8.1 Introduction to the conclusions

The introduction of this thesis formulates the particular aim to obtain a method to support the optimisation of the rotor-nacelle assembly for application in offshore wind farms. To provide a theoretical basis and guidelines for the instantiation of this method, a supporting aim is formulated that addresses the abstract interpretation of the problem. This aim is to obtain the principles of a method to improve system-level trade-offs in non-collaborative development without forcing collaboration between the sub-system designers, but with an increase in engineering contribution.

The analysis of non-collaborative development distinguishes the internal design process, which must be supported by the method, and the external design processes with which there is insufficient collaboration. By comparison of a formal state-space representation of non-collaborative development and a hypothetical collaborative design approach, the differences between the two approaches are identified. The purpose of the method is to minimise the consequences of these differences on the design solution of the internal design process. The main instrument of the method is a tool that emulates collaboration and the external design processes. This emulation provides the means to assess the effect of sub-system design variation on system level properties and value. Several guidelines are provided to derive an implementation of the theory for a particular application. These guidelines address the determination of the functional specification, reduction of scope, determination of domain specific information and generation of the emulation software. The leading proposition of the theory is that emulation of the external design processes based on the suggested guidelines can provide utility, despite its reduction of scope and imperfections. An emulation of offshore wind farm design is made to support the optimisation of rotor-nacelle assemblies. This implementation is used to test the proposition for this particular context. The main hypothesis made during this implementation is that emulation of dimensioning of a fixed offshore wind farm configuration is useful during the preliminary design phase of the rotor-nacelle assembly.

First, conclusions are given concerning the aim and proposition in the context of optimising rotor-nacelle assemblies for application in offshore wind farms. These are
followed by conclusions about the theoretical basis for the use of emulation to support non-collaborative development activities.

8.2 Rotor-nacelle design with emulated offshore wind farm design

The emulation of dimensioning an offshore wind farm with a representative configuration of present-day farms is feasible. The use of heuristic cost models that complement the engineering models to avoid detailed emulation of all design aspects is both necessary and acceptable.

The preliminary dimensioning process can be separated in independent sub-optimisations of the support structure, the electrical infrastructure, the deployment of crew for maintenance and the layout. These sub-optimisations can be performed iteratively to optimise the entire wind farm. However, optimisation may not even be essential in all cases. Using rules of thumb for the initial guess of dimensions in the emulation gives levelised production costs that are close to the optimised solution for wind farm configurations, sizes and sites that are similar to present-day implementations. However, optimisation becomes more necessary for wind farms that deviate from present-day implementations. Furthermore, the initial guess is not sensitive to all changes in rotor-nacelle assembly parameters and may therefore not show all relevant effects of RNA design changes on levelised production costs.

The accuracy of the engineering and economic results of the emulation is sufficient to support optimisation of main parameters of the rotor-nacelle assembly. Absolute accuracy of levelised production costs is in the order of 20%, but correspondence of emulated results with reality depends much on correspondence of the wind farm configuration. More importantly, the response of levelised production costs to changes in main parameters of the rotor-nacelle assembly is clear and in agreement with expectations. Much of the inaccuracy in the absolute value of the levelised production costs drops out in comparative studies of different rotor-nacelle assembly designs.

The use of the emulation has been demonstrated to provide support to the optimisation of the rotor-nacelle parameters. Several main parameters of the rotor-nacelle are shown to have a clear effect on the levelised production costs. The magnitude of this effect and thus of the contribution of the tool to the optimisation is in the order of a few percent. The magnitude of the effect of rotor-nacelle design changes on levelised production costs depends largely on how these parameters affect the wind farm design. Therefore, the same accuracy in the quantitative results cannot be achieved without a model for the wind farm design. Heuristic cost models, also used for this purpose, are less powerful. The emulation proved sensitive to many more parameters of the rotor-nacelle assembly and of the targeted type of wind farms. The emulation enables quick, consistent and quantitative assessment of the effect of design choices. The use of engineering principles helps to identify the origin of benefits and drawbacks and provides additional information to judge validity of the results. Employees of wind turbine manufacturers that have tested the emulation tool confirm the utility of the method.

The prototype of the emulation tool developed for this research has several imperfections. Discontinuous or erratic response of some design variables in the
emulation threatens the ability to optimise the rotor-nacelle assembly. Furthermore, expansion of functionality of the tool and the ability to have more control of processes in the emulation are desired. Potentially, the chosen models and design algorithms can be improved. Wind energy consultants are considered to be in the best position for further developments of the emulation tool. However, engineering software developers can contribute with their expertise in engineering design optimisation that complements the knowledge of wind energy consultants. Furthermore, project developers and companies with experience in turn key projects can provide domain specific knowledge for offshore wind farm design. Wind turbine companies should remain involved in the process of continued development, as users of the tool.

Introduction of the method is expected to require a change in mindset and organisation for the wind turbine manufacturers. The method addresses system-level design choices that were previously outside the scope of the engineering departments. At the same time, it introduces more engineering than previously used in the strategic decisions of a new product development. The method requires and enables closer cooperation between engineering and strategic departments of the company. In addition, users of the method will need to learn the way of working, what confidence they can have in the tool and the interpretation of the results. In particular, they need to become comfortable with working with a tool that works in a domain in which they are no experts.

As a spin off, the tool could be applied in several other applications. Developers of offshore wind farms have already expressed their interest, for instance for site selection, turbine selection, feasibility assessment or preliminary design. The possibilities of the tool to track the effect of uncertainties or design changes on levelised production costs could help prioritise research and innovation and may lead to better insights in the risks of offshore wind energy. However, each application will have different requirements for the tool and will need changes that are not considered to be trivial.

The findings lead to suggestions for activities to follow up the research in various directions. The first direction is the transfer of the method from academy to industry. As mentioned above, this activity is proposed to mainly take place outside the academic world, albeit with support to transfer the knowledge. The second direction is the research of needs and possibilities for improvements of the current implementation. This research would address for instance which inaccuracies are essential, what other models can be used and which design algorithms can and have to be improved. The third direction is the research of possibilities to expand the scope of the application. At the moment, the emulation is most suitable for dimensioning of the rotor-nacelle assembly. This research direction can for instance aim for expansion of the possibilities to support the concept selection of rotor-nacelle assemblies. The fourth direction is a follow up of the spin-off applications. This research would investigate the requirements for these applications, the theoretical basis to support these applications and the consequential further development of the tool.

8.3 Theory for design with emulation of external design processes

The theoretical basis for the support of non-collaborative activities with emulation of external design processes provides guidelines for the instantiation of a method for a
particular domain. These guidelines have been applied to create the emulation tool to apply the method for rotor-nacelle assembly optimisation for offshore wind farms. The guidelines are found to be relevant and helpful during this process and the result demonstrates that this particular instantiation of the theory is useful. This shows the validity of the leading proposition of the theory, which is repeated in the introduction to this chapter.

During the creation of the emulation tool various complementary design theories are used and many decisions are taken without explicit guidance. As a consequence, the findings from this process of creation and testing are idiosyncratic. Nevertheless, some of these findings can be acknowledged to have validity in a wider scope. Furthermore, by putting the particular choices that are made here in perspective of general knowledge about alternative choices gives insight in the potential of the theory for other implementations. The remaining conclusions of this section articulate this insight. It is noted that they are obtained by extrapolation and not supported directly by evidence of the current research.

The first conclusion ties in directly with the previous assessment. Because the guidelines of the theory do not cover all choices that need to be made, the measure of success of new implementations is unknown in advance. Although this is a conclusion that can generally be drawn about design theories, the separation between the abstract formulations of the theory and the practical implementation is considerable in this case. Using the current theory as a foundation, additional guidelines are desired that indicate which directions of development are expected to lead to success and which don’t. This mainly concerns two aspects of the method. First, guidelines are needed that indicate the feasibility of emulation and second guidelines are needed to assess the potential utility at an early stage. In addition, the theory lacks guidelines about the organisation of the work to accommodate the use of emulation in the design process.

A preliminary assessment of feasibility and potential utility reveals that these two aspects are conflicting. Much of the final performance of a system is determined by the choice of concepts and configuration. Alleviating the problems of lack of collaboration while making these choices would therefore be most desirable. However, with the current state of knowledge the implementation of emulation that supports this process is less feasible than implementation that supports optimisation of dimensions for a fixed configuration. In addition, the theory would be most useful for open systems that evolve over time and in which collaboration is more difficult. However, the continuous change of the constituents and configuration of such systems make it more difficult to emulate its design.

Due to the limitations of implementations of the theory, it is less suitable to break the status quo of a fixed configuration that can easily become the consequence of non-collaborative system development. The emulation of external design processes fixes the range of inputs for which the tool will give acceptable results. This effectively limits the design space for the internal design process. The internal design process might want to explore concepts or sizes or applications of the sub-system that are not compatible with the emulation of the external design processes. This will either restrict the liberty of the designers, or the emulation will lose its utility when the internal design runs out of its scope of application.
There are many theories concerning the development of artificial intelligence for design that are useful to make the emulation tool. However, the emulation should work with no or almost no interaction with a knowledgeable user, unlike in many other applications of artificial intelligence in design. The emulation should cover the entire design process, up to the point where the specifications and performance of the solution are known. This increases the difficulty of making a stable and reliable tool. On the other hand, the absolute results of the tool are less important than its response to changes in its inputs. The imperfections in the emulation only have an indirect effect on the success of the internal design process, because many of the systematic errors drop out in comparative study. Even a simple emulation can be expected to have utility, if it provides reasonable information about trends in its response.

A conclusion that relates to the previous one is that the emulated design activities need not be the same as the activity applied in the internal design process in which it is applied. Emulation with a low level of detail may still have utility during a detailed design activity of the internal design. Likewise, emulation of dimensioning of the external design may be useful during concept assessment of the internal design. If the tool only emulates rational activities, it can still be used to guide creative processes. Emulation may prove useful in many situations where the interface parameters between the internal and external design processes are sufficiently well represented by the inputs and outputs of the tool.

Follow up of the theoretical work is necessary to refine the guidelines. These additional guidelines can use much existing knowledge about computer aided design, but future research should establish explicitly which building blocks are suitable in the context of this theory. The guidelines should state which building blocks are expected to meet the requirements of completely autonomous design emulation and in which situations they are useful. New instantiations, for offshore wind energy and for other domains, are to be developed to help generate these guidelines and to test their validity. The goal of this research is to expand the scope of the theory beyond what has been demonstrated with the offshore wind farm design emulation, while creating clear expectations of what can be achieved with existing design knowledge.
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## Appendix A Constructs of the theory

This appendix defines important terms used in the theory in order to avoid confusion about their interpretation. The definitions are chosen to best describe the meaning of the terms as they are used in this theory and not to imply a consensus of the interpretations in literature. The terms are sorted alphabetically.

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Collaborative design</strong></td>
<td>The generation of (sub-) system specifications by groups who effectively use bidirectional communication to achieve high performance of the total system.</td>
</tr>
<tr>
<td><strong>Collaborative design paradigm</strong></td>
<td>Pattern of design activities and attributes that determine the communication between design groups and the methods of collaboration engineering.</td>
</tr>
<tr>
<td><strong>Collaboration engineers/engineering</strong></td>
<td>People or processes whose purpose is maximising effectiveness of the composition of sub-systems in meeting the overall needs for the system.</td>
</tr>
<tr>
<td><strong>Communication</strong></td>
<td>Any transfer of a sub-state of the domain of the mind or expressions thereof in the domain of material reality.</td>
</tr>
<tr>
<td><strong>Domain</strong></td>
<td>The field encompassed by a part of the overall state vector and its related processes.</td>
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<tr>
<td><strong>Emulation</strong></td>
<td>The process of imitation of external design groups and collaboration engineers that allows the target group to have access to similar information as in collaborative design.</td>
</tr>
<tr>
<td><strong>External</strong></td>
<td>Outside the domain of the target design group.</td>
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<tr>
<td><strong>Interface</strong></td>
<td>Format of graphical, textual or other means of interaction between designers of the target design group and the emulation.</td>
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<tr>
<td><strong>Internal</strong></td>
<td>In the domain of the target design group.</td>
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<tr>
<td><strong>Non-collaborative development</strong></td>
<td>The development of a system or system specifications in which some sub-system specifications are generated without collaboration with groups that design other sub systems.</td>
</tr>
<tr>
<td><strong>Sub-system specification</strong></td>
<td>A detailed description of the particulars of the sub system, giving the dimensions, materials, quantities, etc., together with directions to be followed by the manufacturer and operator.</td>
</tr>
<tr>
<td><strong>Target design group</strong></td>
<td>The group designing part of a system in a non-collaborative development for which the proposed method is intended.</td>
</tr>
</tbody>
</table>
Appendix B Objective function separation

Table B-1 shows which cost components are modelled and when their values are updated. Table B-2 shows this for the energy capture efficiencies.

<table>
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<tr>
<th>Cost component</th>
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<td>Procurement</td>
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<tr>
<td>Infield cable</td>
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<td>x</td>
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<tr>
<td>Offshore platform and measuring tower</td>
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<td></td>
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<td></td>
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<tr>
<td>Rotor-nacelle assemblies</td>
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</tr>
</tbody>
</table>

1. Fixed values, doesn’t need to be updated
2. Update when user input changes
3. Update when other relevant cost components change (summation or percentage)
4. Update when support structures are redesigned
5. Update when transformers are redesigned
6. Update when infield cables are redesigned
7. Update when transmission cable is redesigned
8. Update when maintenance is redesigned
9. Update when layout is redesigned

Table B-2 Efficiency contributions and when they need to be updated

<table>
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<tr>
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<th>3</th>
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<tbody>
<tr>
<td>Energy yield solitary turbine</td>
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<td>x</td>
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<tr>
<td>Electrical efficiency</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Transformer losses</td>
<td></td>
<td>x</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Infield cable losses</td>
<td></td>
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<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shunt reactor losses</td>
<td></td>
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<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Transmission cable losses</td>
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<td></td>
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</tr>
<tr>
<td>Availability</td>
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<td>x</td>
</tr>
<tr>
<td>Array efficiency</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
</tbody>
</table>

1. Update when support structures are redesigned
2. Update when transformers are redesigned
3. Update when infield cables are redesigned
4. Update when transmission cable is redesigned
5. Update when maintenance is redesigned
6. Update when layout is redesigned
Appendix C Mathematical descriptions of cost models

Table C-1 shows the inflations rates and exchange rates used to convert and actualise cost information. Not all currencies in this table are visible in the cost models of Table C-2, because these are only used to convert data and models that are used for calibration of the models in Table C-2.

<table>
<thead>
<tr>
<th>Currency</th>
<th>Annual inflation rate (%)</th>
<th>Exchange rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>USD</td>
<td>2.57</td>
<td>0.742</td>
</tr>
<tr>
<td>GBP</td>
<td>2.55</td>
<td>1.166</td>
</tr>
<tr>
<td>DKK</td>
<td>1.84</td>
<td>0.134</td>
</tr>
<tr>
<td>SEK</td>
<td>2.03</td>
<td>0.110</td>
</tr>
<tr>
<td>NOK</td>
<td>1.95</td>
<td>0.129</td>
</tr>
<tr>
<td>Euro</td>
<td>2.16</td>
<td>1.0</td>
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</tbody>
</table>

Table C-2 gives the mathematical descriptions of the used cost models and the currency in which the result of the model is expressed. All parameters in the equations are in basic SI-units, so e.g. in W and not in kW, unless specified otherwise. Times are in hours, masses are in kg, electricity production is in Wh and power of reactive power compensation is in VAr. The symbols are explained in the list of symbols.

<table>
<thead>
<tr>
<th>Cost item</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Investment costs</strong></td>
<td></td>
</tr>
<tr>
<td>Management</td>
<td>$0.03 \cdot C_{\text{capital}}$</td>
</tr>
<tr>
<td>Project development</td>
<td></td>
</tr>
<tr>
<td>Engineering</td>
<td>$0.037 \cdot P_{\text{farm, rated}}$</td>
</tr>
<tr>
<td><strong>Investment costs – Procurement – Rotor-nacelle</strong></td>
<td></td>
</tr>
<tr>
<td>Purchase</td>
<td>$C_{\text{RNA}} \cdot N_t$</td>
</tr>
<tr>
<td>Warranty</td>
<td>$f_{\text{warranty}} \cdot C_{\text{RNA}} \cdot N_t$</td>
</tr>
<tr>
<td><strong>Investment costs – Procurement – Support structure</strong></td>
<td></td>
</tr>
<tr>
<td>Tower</td>
<td>$2.04 \cdot m_{\text{tower}} \cdot N_t$</td>
</tr>
<tr>
<td>Transition piece</td>
<td>$3.75 \cdot m_{\text{transition piece}} \cdot N_t$</td>
</tr>
<tr>
<td>Boat landing</td>
<td>$60,000 \cdot N_t$</td>
</tr>
<tr>
<td>Grout</td>
<td>$0.1 \cdot m_{\text{grout}} \cdot N_t$</td>
</tr>
<tr>
<td>Monopile</td>
<td>$2.25 \cdot m_{\text{pile}} \cdot N_t$</td>
</tr>
<tr>
<td>Scour protection*</td>
<td>$211 \cdot V_{\text{scour protection}} \cdot N_t$</td>
</tr>
</tbody>
</table>
### Investment costs – Procurement – Electrical system

<table>
<thead>
<tr>
<th>Cost item</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infield cable</td>
<td>$50 + 2.3 \cdot (5 \cdot m_{copper} + 15 \cdot m_{insulation})$</td>
</tr>
<tr>
<td>Transmission cable</td>
<td>$50 + 2.3 \cdot (5 \cdot m_{copper} + 15 \cdot m_{insulation})$</td>
</tr>
<tr>
<td>Shunt reactor</td>
<td>$0.807 \cdot (P_{shunt, onshore}^{0.7513} + P_{shunt, offshore}^{0.7513})$</td>
</tr>
<tr>
<td>Transformer</td>
<td>$(3.06 \cdot 10^{-3} \cdot P_{turbine, rated} + 810) \cdot e^{0.039 \cdot N_t} +$</td>
</tr>
<tr>
<td></td>
<td>$(1.16 \cdot P_{farm, rated}^{0.7513}) \cdot (e^{0.039 \cdot N_{turbine}} + e^{0.039 \cdot N_{offshore}})$</td>
</tr>
<tr>
<td>Switch gear</td>
<td>$(100.33 \cdot 10^3 + 2.8726 \cdot V_{L, infield}) \cdot N_{cubicles, turbines} +$</td>
</tr>
<tr>
<td></td>
<td>$(320 \cdot 10^3 + 6 \cdot V_{L, infield}) \cdot N_{cubicles, collection} +$</td>
</tr>
<tr>
<td></td>
<td>$(320 \cdot 10^3 + 6 \cdot V_{L, transmission}) \cdot N_{cubicles, transmission} +$</td>
</tr>
<tr>
<td></td>
<td>$(320 \cdot 10^3 + 6 \cdot V_{L, grid}) \cdot N_{cubicles, connection}$</td>
</tr>
</tbody>
</table>

### Investment costs – Procurement – Auxiliary

<table>
<thead>
<tr>
<th>Cost item</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measuring tower</td>
<td>2,050,000</td>
</tr>
<tr>
<td>Offshore premises</td>
<td>1,500,000</td>
</tr>
<tr>
<td>Offshore platform</td>
<td>$2 \left(0.4 \cdot 10^{-3} \cdot m_{jacket}^2 - 50 \cdot m_{jacket} - 80 \cdot 10^6 \right)$ with:</td>
</tr>
<tr>
<td>(Including installation)</td>
<td>$m_{jacket} = 582 \cdot d_{water}^{0.19} \cdot \left(3 \cdot 10^{-3} \cdot P_{farm, rated} + 0.5 \cdot 10^6 \right)^{0.48}$</td>
</tr>
</tbody>
</table>

### Investment costs – Installation

<table>
<thead>
<tr>
<th>Cost item</th>
<th>Model</th>
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</thead>
<tbody>
<tr>
<td>Foundations</td>
<td>$1.4 \cdot m_{pile} \cdot N_t$</td>
</tr>
<tr>
<td>Offshore transport</td>
<td>$5.84 \cdot 10^{-3} \cdot D + 0.4) \cdot L + 0.486 \cdot D^{2.64}$</td>
</tr>
<tr>
<td>Offshore works</td>
<td>$3.4 \cdot 10^3 \cdot (h_{hub} + 50) \cdot N_t$</td>
</tr>
</tbody>
</table>

### Investment costs – Installation – Electrical system

<table>
<thead>
<tr>
<th>Cost item</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infield cable</td>
<td>500,000 $(+) 169 \cdot l$</td>
</tr>
<tr>
<td>Transmission cable</td>
<td>500,000 $(+) 178 \cdot l$</td>
</tr>
<tr>
<td>Dune crossing</td>
<td>1,200,000</td>
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</tbody>
</table>

### Investment costs – Installation – Auxiliary

<table>
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<tr>
<td>Meteo tower</td>
<td>550,000</td>
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<tr>
<td>Harbour use</td>
<td>$0.02 \cdot P_{farm, rated}$</td>
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</table>

### Operation and maintenance costs (O&M costs are per year)

<table>
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<tr>
<th>Cost item</th>
<th>Model</th>
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<tbody>
<tr>
<td>Management</td>
<td>$0.03 \cdot C_{O&amp;M}$</td>
</tr>
<tr>
<td>Cost item</td>
<td>Model</td>
</tr>
<tr>
<td>-----------------------------------------------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td><strong>Operation and maintenance costs – Maintenance (O&amp;M costs are per year)</strong></td>
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</tr>
<tr>
<td>Consumables (repairs) [Euro actual]</td>
<td>$\sum_{\text{failure type } j} N_{f,\text{total }, j} \cdot C_{\text{repair }, j}$</td>
</tr>
<tr>
<td>Consumables (preventive maint.) [Euro actual]</td>
<td>$N_{pm} \cdot C_{pm}$</td>
</tr>
<tr>
<td>Access vessels [USD 2003]</td>
<td>$T_v \cdot C_v$</td>
</tr>
</tbody>
</table>
| Personnel [Euro 2002]                         | $70 \cdot 365 \cdot N_p \cdot N_{\text{crew}} \cdot N_s \cdot T_{\text{shift}} \cdot f_{\text{shift length}} \cdot f_{\text{shift rotation}}$
  \[
  \begin{align*}
    f_{\text{shift length}} &= 1 \quad (T_s \leq 8) \\
    f_{\text{shift length}} &= 1.2 - 1.6/T_s \quad (T_s > 8) \\
    f_{\text{shift rotation}} &= 1 \quad (N_s = 1) \\
    f_{\text{shift rotation}} &= 1.15 \quad (N_s > 1)
  \end{align*}
\]
| Lifting equipment rental [USD 2010]            | $54 \cdot (h_{\text{hub}} + 50) \cdot (100 \cdot N_{m_{\text{hub}}} + T_{\text{lift}})$                                           |
| Subsea inspection [Euro 2003]                 | $7,000 \cdot N_t$                                                                                                                   |
| **Operation and maintenance costs – Operation (O&M costs are per year)**                    |                                                                                                                                         |
| Insurance [Euro actual]                       | $0.01 \cdot C_{\text{RNA}} \cdot N_t$                                                                                              |
| Grid charge [Euro 2009]                       | $3 \cdot 10^{-6} \cdot E_t$                                                                                                       |
| Bottom lease [Euro 2009]                      | $60.7 \cdot 10^{-3} \cdot A_{farm}$                                                                                               |
| Administration [Euro 2012]                    | $1,000,000$                                                                                                                         |
| **Decommissioning costs**                     |                                                                                                                                         |
| Management [Euro actual]                      | $0.03 \cdot C_{\text{decommissioning}}$                                                                                           |
| **Decommissioning costs – Removal**           |                                                                                                                                         |
| Rotor-nacelle assemblies [Euro actual]        | $0.91 \cdot C_{\text{offshore works}}$                                                                                           |
| Foundations [Euro actual]                     | $0.91 \cdot C_{\text{foundation installation}}$                                                                                   |
| Infield cable [USD 2010]                      | $53 \cdot l$                                                                                                                       |
| Transmission cable [USD 2010]                 | $49 \cdot l$                                                                                                                       |
| Offshore platform and meteo tower [USD 2010]  | $665,000$                                                                                                                          |
| Scour protection [USD 2010]                   | $33 \cdot V_{\text{scour protection}} \cdot N_t$                                                                                   |
| Site clearance [USD 2010]                     | $16,000 \cdot N_t$                                                                                                                 |
| **Decommissioning costs – Disposal**          |                                                                                                                                         |
| Rotor-nacelle assemblies [USD 2010]           | $150 \cdot m_{RNA} \cdot N_t$                                                                                                     |

Appendix D Mathematical descriptions used in physical models

Table D-1 gives the mathematical descriptions of the physical models that are used in the tool. Symbols are not explained in this appendix, but their meaning can be found in the list of symbols. Symbols may differ from those in the references for disambiguation or consistency in the context of this thesis.

<table>
<thead>
<tr>
<th>Table D-1 Mathematical descriptions of physical models</th>
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<td><strong>Site conditions</strong></td>
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<td>Wind speed at height ( h )</td>
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<tr>
<td>Wave period</td>
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<tr>
<td>Dispersion relation (to determine wave number)</td>
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<td>Breaking wave limit</td>
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<tr>
<td>Amplitude of seabed orbital velocity and motion</td>
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<tr>
<td>Keulegan-Carpenter number</td>
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<tr>
<td>Amplification of wave water particle velocity due to horse shoe vortex around monopile</td>
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<tr>
<td><strong>Gravity loading</strong></td>
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<tr>
<td>Gravity on tapered cylinder of constant thickness</td>
</tr>
</tbody>
</table>

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| Model | 
|---|---|
| If base and top diameter are equal $b$ | $F_g = -\pi g \rho \frac{1}{4} \left( D^2 - (D - 2t)^2 \right) z \bigg|_{z_w}$ |
| Aerodynamic loading | 
| Drag force on tapered cylinder in wind shear $b$ | $F_d = \frac{1}{2} \rho c_d V_{ref}^2 \left( \frac{1}{h_{ref}} \right)^{2\alpha}$ 
| & $\left( \frac{D_{base} - \frac{z_{base} (D_{top} - D_{base})}{l}}{l} \frac{1}{2\alpha + 1} z^{2\alpha + 1} \right) +$ 
| & $\left( \frac{D_{top} - D_{base}}{l} \frac{1}{2\alpha + 2} z^{2\alpha + 2} \right)_{z_w}$ |
| Moment relative to $z$-coordinate $c$ due to drag force on tapered cylinder in wind shear $b$ | $M_d = -z_{ref} F_d + \frac{1}{2} \rho c_d V_{ref}^2 \left( \frac{1}{h_{ref}} \right)^{2\alpha}$ 
| & $\left( \frac{D_{base} - \frac{z_{base} (D_{top} - D_{base})}{l}}{l} \frac{1}{2\alpha + 2} z^{2\alpha + 2} \right)_{z_w}$ + 
| & $\left( \frac{D_{top} - D_{base}}{l} \frac{1}{2\alpha + 3} z^{2\alpha + 3} \right)_{z_w}$ |
| Hydrodynamic loading | 
| Amplitude of water elevation $\hat{\zeta} = H/2$ | $\hat{F}_j = c_m \rho \pi D^2 g \frac{\tanh kd}{\sinh kd} \sinh k(z + d) \bigg|_{z_w}$ 
| Inertia force on uniform cylinder $b$ | $\hat{M}_i = -z_{ref} \hat{F}_j +$ 
| & $c_m \rho \pi D^2 g \frac{\tanh kd}{\sinh kd} \left( z \sinh k(z + d) - \frac{1}{k} \cosh k(z + d) \right) \bigg|_{z_w}$ |
| Moment relative to $z$-coordinate $c$ due to inertia force on uniform cylinder $b$ | $\hat{M}_i = -z_{ref} \hat{F}_j +$ 
<p>| &amp; $c_m \rho \pi D^2 g \frac{\tanh kd}{\sinh kd} \left( z \sinh k(z + d) - \frac{1}{k} \cosh k(z + d) \right) \bigg|_{z_w}$ |
| Drag force on uniform cylinder $b$ | $\hat{F}<em>d = c_d \frac{1}{2} \rho D^2 g \frac{2}{\sinh 2kd} \left( \frac{\sinh 2k(z + d)}{k(z + d)} \right) \bigg|</em>{z_w}$ |</p>
<table>
<thead>
<tr>
<th>Aspect</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moment relative to z-coordinate ( c ) due to drag force on uniform cylinder ( b )</td>
<td>[ M_d = -z_r \dot{F}_D + c_d \frac{1}{2} \rho D^2 \dot{z} g \frac{2}{\sinh 2kd} \left( \frac{\sinh(2k(z + d))}{4} + \frac{k(z + d)}{2} \right) \left( \frac{\cosh(2k(z + d)) + \frac{k(z + d)}{2}}{4k} \right) ]</td>
</tr>
</tbody>
</table>

**Mechanics**

Total structure height \( H = h_{hub} + d_{water} \)

Tower wall thickness at which Euler buckling would occur \( t = \frac{4|F_z|H^2}{\pi^3 E \cdot D_{tower}^3} \)

Stress in monopile due to axial load \( \sigma_{axial} = \frac{|F_z|}{\frac{1}{4} \pi \left( D_{pile}^2 - (D_{pile} - 2t_{pile})^2 \right)} \)

Stress in monopile due to bending \( \sigma_{bending} = \frac{|M_y|D_{pile}}{2I} \) with: \( I = \frac{D_{pile}^4 - (D_{pile} - 2t_{pile})^4}{64} \)

Maximum stress in monopile \( \sigma_{total} = \sigma_{axial} + \sigma_{bending} \)

Stress in tower and transition piece due to axial load \( \sigma_{axial} = \frac{|F_z|}{\pi Dt} \)

Stress in tower and transition piece due to bending \( \sigma_{bending} = \frac{|M_y|D}{2I} \) with: \( I = \frac{1}{8} \pi D^3 t \)

Reduction factor \( \varepsilon = \frac{\varepsilon_a \sigma_{axial} + \varepsilon_b \sigma_{bending}}{\sigma_{axial} + \sigma_{bending}} \) with:

\[ \varepsilon_a = \frac{0.83}{\sqrt{1 + 0.01 \frac{D}{2t}}} \] and \( \varepsilon_b = 0.1887 + 0.8113 \cdot \varepsilon_a \)

Critical compressive stress according to theory of elasticity \( \sigma_{el} = \frac{E_d}{2t \sqrt{3(1 - \nu^2)}} \)

Relative slenderness ratio for local buckling \( \lambda_a = \frac{f_{yd}}{\varepsilon \sigma_{el}} \)

Critical compressive stress \( \sigma_{cr} = f_{yd} \) when \( H \leq D \sqrt{\frac{D}{t}} \) or \( \lambda_a \leq 0.3 \) or:

\[ \sigma_{cr} = (1.5 - 0.913 \sqrt{\lambda_a}) f_{yd} \] when \( 0.3 < \lambda_a \leq 1 \)
<table>
<thead>
<tr>
<th>Aspect</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Euler force for cantilever beam according to theory of elasticity^{87}</td>
<td>( N_{el} = \frac{1}{4} \pi^2 E_d I )</td>
</tr>
<tr>
<td>Relative slenderness ratio for global stability^{87}</td>
<td>( \lambda_r = \frac{\sigma_{cr}}{\sqrt{\frac{N_{el}}{\pi D t}}} )</td>
</tr>
<tr>
<td>Core radius of a tube^{87}</td>
<td>( k = \frac{D}{4} )</td>
</tr>
<tr>
<td>Equivalent geometrical imperfection^{87}</td>
<td>( e = \max \left( 0, 0.34 \cdot \left( \lambda_r - 0.2 \right) k \right) ) and if ( e &gt; \frac{2}{1000} H ) then:( e = e + \left( e - \frac{2}{1000} H \right) )</td>
</tr>
<tr>
<td>Combined stress for comparison with critical stress^{87}</td>
<td>( \sigma_{total} = \frac{N_d}{\pi D t} + \frac{N_{el}}{N_{el} - N_d} \left[ \frac{M_y}{\pi d^2 t} + \frac{N_d e}{4 \pi D^2 t} \right] )</td>
</tr>
<tr>
<td>Geophysics</td>
<td></td>
</tr>
<tr>
<td>Clamping depth for lateral force (implicit)^{297}</td>
<td>( \left( K_p - K_a \right) \gamma^1 D_{pile} \cdot d_{clamping}^2 = 6 \left( F_{lat} + \frac{M_{rot}}{d_{clamping}} \right) )</td>
</tr>
<tr>
<td>Rocks</td>
<td></td>
</tr>
<tr>
<td>( d_{15} ) and ( d_{85} ) of armour layer as function of ( d_{50}^{b} )</td>
<td>( d_{15} = 0.8 \cdot d_{50}, \ d_{85} = 1.2 \cdot d_{50} )</td>
</tr>
<tr>
<td>( d_{15} ) and ( d_{50} ) of filter layer as function of ( d_{85}^{b} )</td>
<td>( d_{50} = 0.7 \cdot d_{85}, \ d_{15} = 0.4 \cdot d_{85} )</td>
</tr>
<tr>
<td>Hydrology</td>
<td></td>
</tr>
<tr>
<td>Dimensionless grain size^{258, 306}</td>
<td>( D_s = \left[ \frac{g (s-1)}{v_w^2} \right]^{\frac{1}{3}} d_{50} ) with ( s = \rho_s/\rho_w )</td>
</tr>
<tr>
<td>Critical Shields parameter^{258, 306}</td>
<td>( \theta_{cr} = 0.30 + 0.055 \left[ 1 - e^{-0.20 D_s} \right] )</td>
</tr>
</tbody>
</table>
| Wave friction factor^{258}                                          | \( f_w = \max \left( f_{wr}, f_{ws} \right) \), with:\(\begin{cases} f_{ws} = 2 \cdot R_w^{-0.5} \quad \left( R_w < 1 \cdot 10^{-5} \right) \\
 f_{ws} = 0.0521 \cdot R_w^{-0.187} \quad \left( R_w \geq 1 \cdot 10^{-5} \right) \end{cases} \)
(\( f_{wr} = 0.237 \cdot r_r^{-0.52} \) using:\( r_r = \frac{A_w}{k_s}, \ k_s = 2.5 d_{40}, \ R_w = \frac{U_w A_w}{v_w} \)) |
<table>
<thead>
<tr>
<th>Aspect</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shear stress due to current</strong>&lt;sup&gt;306&lt;/sup&gt;</td>
<td>[ \tau_c = \rho_v c_d U^2 \text{ with: } c_d = \frac{0.40}{1 + \ln \left( \frac{z_0}{d_{\text{water}}} \right)} \text{ and:} ]</td>
</tr>
<tr>
<td></td>
<td>[ z_0 = \frac{2.5 d_{50}}{30} ]</td>
</tr>
<tr>
<td><strong>Shear stress due to waves</strong>&lt;sup&gt;258&lt;/sup&gt;</td>
<td>[ \tau_w = 0.5 \rho_w f_w U_w^2 ]</td>
</tr>
<tr>
<td><strong>The combined characteristic shear stress of current and waves</strong>&lt;sup&gt;258, 306&lt;/sup&gt;</td>
<td>[ \tau_{\text{max}} = \sqrt{\left( \tau_m + \tau_w \cos \phi \right)^2 + \left( \tau_w \sin \phi \right)^2} \text{ with:} ]</td>
</tr>
<tr>
<td></td>
<td>[ \frac{\tau_{\text{max}}}{\tau_c} = 1 + 1.2 \left( \frac{\tau_w}{\tau_c + \tau_w} \right)^{3.2} ]</td>
</tr>
<tr>
<td><strong>Array efficiency</strong></td>
<td><em>(Not published: straightforward derivations)</em></td>
</tr>
<tr>
<td><strong>Geometric equations of angles of incidence, distances and radii</strong></td>
<td><em>(Not published: straightforward derivations)</em></td>
</tr>
<tr>
<td><strong>Single turbine wake</strong>&lt;sup&gt;170&lt;/sup&gt;</td>
<td>[ \left( 1 - \frac{V_i}{V_0} \right) = \frac{1 - \sqrt{1 - c_T}}{\left( 1 + \frac{2kx}{D_{\text{rotor}}} \right)}^2 ]</td>
</tr>
<tr>
<td><strong>Mixed wakes</strong>&lt;sup&gt;210&lt;/sup&gt;</td>
<td>[ \left( 1 - \frac{V_m}{V_0} \right)^2 = \sum_{i=1}^{N_{\text{wake}}} \left( 1 - \frac{V_i}{V_0} \right)^2 ]</td>
</tr>
<tr>
<td><strong>Area of incidence of partial wake or multiple wake overlap</strong>&lt;sup&gt;304&lt;/sup&gt;</td>
<td>[ A_{\text{wake}} = r^2 \cos \left( \frac{d^2 + r^2 - R^2}{2dr} \right) + R^2 \cos \left( \frac{d^2 + R^2 - r^2}{2dR} \right) - \frac{1}{2} \sqrt{(-d + r + R)(d + r - R)(d - r + R)(d + r + R)} ]</td>
</tr>
<tr>
<td><strong>Electricity</strong></td>
<td><em>(Not published: straightforward derivations)</em></td>
</tr>
<tr>
<td><strong>Active current in cable</strong></td>
<td>[ I_{\text{active}} = \frac{N_{\text{t, branch}} P_{\text{turbine}}}{\sqrt{3} \cdot V_L} ]</td>
</tr>
<tr>
<td><strong>Capacitance per unit length</strong></td>
<td>[ C' = \frac{2 \pi \varepsilon_0 \varepsilon_r}{\ln \left( \frac{D_i}{D_{\text{co}}} \right)} ]</td>
</tr>
<tr>
<td><strong>Reactive current in cable</strong></td>
<td>[ I_{\text{reactive}} (x') = 2 \pi fC' (l - x') \frac{V_L}{\sqrt{3}} ]</td>
</tr>
<tr>
<td><strong>Total current in cable</strong></td>
<td>[ I_{\text{total}} (x) = \sqrt{I_{\text{active}}^2 (x) + I_{\text{reactive}}^2 (x)} ]</td>
</tr>
<tr>
<td><strong>Geometrical factor</strong> (fit to graph of Anders&lt;sup&gt;11&lt;/sup&gt;)</td>
<td>[ G = -0.36 \left( \frac{I_i}{D_c} \right)^4 + 1.9 \left( \frac{I_i}{D_c} \right)^3 - 3.7 \left( \frac{I_i}{D_c} \right)^2 + 3.8 \left( \frac{I_i}{D_c} \right) + 0.24 ]</td>
</tr>
<tr>
<td>Aspect</td>
<td>Model</td>
</tr>
<tr>
<td>--------------------------------------------</td>
<td>-----------------------------------------------------------------------</td>
</tr>
<tr>
<td><strong>Screening factor (fit to graph of Anders)</strong></td>
<td>$K = \left( 0.16 \frac{t_s}{D_c} - 0.65 \right) \ln (T_s) + \left( 0.93 \frac{t_s}{D_c} + 0.84 \right)$ with: $T_s = \frac{t_s \rho_s}{D_c \rho_i}$</td>
</tr>
<tr>
<td><strong>Thermal resistances</strong></td>
<td>$T_1 = \max \left( K \frac{\rho_s}{2\pi} G, \frac{\rho_i}{2\pi} \ln \left( 1 + \frac{2t_s}{D_c} \right) \right)$</td>
</tr>
<tr>
<td></td>
<td>$T_2 = \frac{\rho_b}{2\pi} \ln \left( 1 + \frac{2t_b}{D_{bi}} \right)$</td>
</tr>
<tr>
<td></td>
<td>$T_3 = \frac{\rho_{ox}}{2\pi} \ln \left( 1 + \frac{2t_{ox}}{D_a} \right)$</td>
</tr>
<tr>
<td></td>
<td>$T_4 = \frac{\rho_{soil}}{2\pi} \ln \left( \mu + \sqrt{\mu^2 + 1} \right)$ with: $\mu = \frac{2d_{burial}}{D_{soil}}$</td>
</tr>
<tr>
<td><strong>Temperature difference between conductor and environment</strong></td>
<td>$\Delta \theta(x) = \left( I_{\text{total}}^2(x) R_{\theta} + \frac{1}{2} W_d(x) \right) T_1 + \left( I_{\text{total}}^2(x) R_{\theta}(1 + \lambda_1) \right) n T_2 + \left( I_{\text{total}}^2(x) R_{\theta}(1 + \lambda_1 + \lambda_2) \right) n (T_3 + T_4)$</td>
</tr>
<tr>
<td><strong>Maximum temperature in insulation of cable</strong></td>
<td>$\theta_{\text{insulation}} = \theta_{\text{ambient}} + \Delta \theta$</td>
</tr>
<tr>
<td><strong>Resistance of cable at 20°</strong></td>
<td>$R_{20} = \frac{\rho_{20}}{A_x}$</td>
</tr>
<tr>
<td><strong>Resistance of conductor at operating temperature, excluding sheath and armour loss</strong></td>
<td>$R_{\theta} = R_{20} \left( 1 + \alpha_{\theta} (\theta - 20) \right)$</td>
</tr>
<tr>
<td><strong>Resistance of conductor at operating temperature, including sheath and armour loss</strong></td>
<td>$R'(x) = R_{\theta} \left( 1 + \lambda_1 + \lambda_2 \right)$</td>
</tr>
<tr>
<td><strong>Resistive loss per unit length</strong></td>
<td>$W_r(x) = n_x I_{\text{total}}^2(x) R'(x)$</td>
</tr>
<tr>
<td><strong>Dielectric loss per unit length</strong></td>
<td>$W_d = 2\pi n_x fC' \frac{V^2}{3} \tan \delta$</td>
</tr>
<tr>
<td><strong>Total cable loss per unit length</strong></td>
<td>$W_{\text{total}}(x) = W_d + W_r(x)$</td>
</tr>
</tbody>
</table>
## Integration of cable loss per segment

Integration of cable loss per segment:

\[ P_{\text{loss,cable}} = \frac{a l^3}{3} + \frac{b l^2}{2} + cl \]

with:

\[ a = \sum_k \prod_{j \neq k} \frac{y_k}{x_k - x_j}, \quad b = -\sum_k \prod_{j \neq k} \frac{y_k}{x_k - x_j} \sum x_j, \]
\[ c = \sum_k \left\{ \prod_{j \neq k} \frac{y_k}{x_k - x_j} \prod x_j \right\} \]

(x and y are the distance along the cable segment and the local loss per meter, respectively. The indices indicate begin, middle and end of the cable.)

## Power rating of shunt reactor

Power rating of shunt reactor:

\[ P_{\text{shunt}} = \frac{V^2_{\text{L,transmission}}}{2\pi fL} \]

## Reactive current in shunt reactor

Reactive current in shunt reactor:

\[ I_{\text{reactive,shunt}} = \frac{1}{2\pi fL} \frac{V_{\text{L,transmission}}}{\sqrt{3}} \]

## Power loss in shunt reactor

Power loss in shunt reactor:

\[ P_{\text{loss,shunt}} = (1 - \eta_{\text{shunt}}) P_{\text{shunt}} \]

## No-load loss in the transformer

No-load loss in the transformer:

\[ P_{\text{loss, no-load}} = 0.37 \cdot 10^{-3} \cdot (P_{\text{trafo, rated}} - 3.5 \cdot 10^6) + 2 \cdot 10^3 \]

## Loaded loss in the transformer

Loaded loss in the transformer:

\[ P_{\text{loss, full-load}} = 4.0 \cdot 10^{-12} (P_{\text{trafo, rated}} - 3.5 \cdot 10^6)^2 + 2.6 \cdot 10^{-3} (P_{\text{trafo, rated}} - 3.5 \cdot 10^6) + 13 \cdot 10^3 \]

## Annual loss in electrical infrastructure

Annual loss in electrical infrastructure (Adapted from Schoenmakers):

\[ E_{\text{loss, e}} = \int \left( \frac{P_{\text{loss, e, no-load}}}{P_{\text{turbine, rated}}} \right)^+ \left( \frac{P_{\text{turbine}}(V)}{P_{\text{turbine, rated}}} \right)^2 P_{\text{loss, e, full-load}} f(V) \Delta V \]

## Maintenance

**Storm fraction**

\[ f_s = \frac{1}{1 + \left( \frac{H_s}{H_{s, ref}} \right)^b \cdot \left( \frac{1}{f_{s, ref}} - 1 \right)}, \quad \text{with} \quad b = 2.3 \]

**Scale factor of storm length**

\[ c_{T_{\text{storm}}} = \left( \frac{H_s}{H_{s, ref}} \right)^b c_{T_{\text{storm,ref}}}, \quad \text{with} \quad b = -1.5 \]

**Probability density function of storm length**

\[ p(T_{\text{storm}}) = \frac{k_{T_{\text{storm}}}}{c_{T_{\text{storm}}}} \left( \frac{T_{\text{storm}}}{c_{T_{\text{storm}}}} \right)^{k_{T_{\text{storm}}}-1} e^{-\left( \frac{T_{\text{storm}}}{c_{T_{\text{storm}}}} \right)^{k_{T_{\text{storm}}}}} \]

**Average storm length**

\[ E(T_{\text{storm}}) = c_{T_{\text{storm}}} \Gamma \left( 1 + \frac{1}{k_{T_{\text{storm}}}} \right) \]
<table>
<thead>
<tr>
<th>Aspect</th>
<th>Model</th>
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</thead>
<tbody>
<tr>
<td>Number of storms during lifetime&lt;sup&gt;b&lt;/sup&gt;</td>
<td>( N_{\text{storms}} = \frac{f_s \cdot T_{\text{life}}}{E(T_{\text{storm}})} )</td>
</tr>
<tr>
<td>Hazard rate for failure of type ( j )</td>
<td>( h_j = \frac{1}{MTBF_j} )</td>
</tr>
<tr>
<td>Time to process diagnosis information of failure of type ( j )</td>
<td>( T_{pd,j} = T_{\text{day}} / N_s ) when ( T_{\text{diagnose},j} &gt; 0 ) and no lifting is needed, else: ( T_{pd,j} = T_{\text{day}} )</td>
</tr>
<tr>
<td>Downtime during preparation of repair of failure of type ( j )</td>
<td>( T_{\text{prepare},j} = \max \left( T_{ip,j}, T_{pd,j} \right) ) when no lifting is needed, else: ( T_{\text{prepare},j} = 0 )</td>
</tr>
<tr>
<td>Travel time to and from farm&lt;sup&gt;b&lt;/sup&gt;</td>
<td>( T_{t,to} = \frac{d_b}{V_v} )</td>
</tr>
<tr>
<td>Travel time in farm&lt;sup&gt;a&lt;/sup&gt;</td>
<td>( T_{t,in} \approx \max (s_e \cdot (N_e - 1), s_c \cdot (N_c - 1)) / 2V_v )</td>
</tr>
<tr>
<td>Time of work in progress for repair of failure of type ( j ) without preparation and waiting for crew&lt;sup&gt;b&lt;/sup&gt;</td>
<td>( T_{\text{wip},j} = T_{\text{day}} / N_s \cdot \frac{T_{\text{diagnose},j} + T_{\text{fix},j} + T_{t,in}}{\eta_{\text{shift}} \left( T_{t,to} - 2(T_{t,to} + T_{t,in}) \right)} )</td>
</tr>
<tr>
<td>Expected value of steady state downtime due to preparation&lt;sup&gt;b&lt;/sup&gt;</td>
<td>( E(T_{d,\text{prepare},j}) = \frac{N_j \cdot T_{\text{life}} \cdot h_j \cdot T_{\text{prepare},j}}{1 + \sum_j h_j \left( T_{\text{prepare},j} + T_{d,\text{wip},j} \right)} )</td>
</tr>
<tr>
<td>Expected value of steady state downtime due to work in progress&lt;sup&gt;b&lt;/sup&gt;</td>
<td>( E(T_{d,\text{wip},j}) = \frac{N_j \cdot T_{\text{life}} \cdot h_j \cdot T_{\text{wip},j}}{1 + \sum_j h_j \left( T_{\text{prepare},j} + T_{d,\text{wip},j} \right)} )</td>
</tr>
<tr>
<td>Probability of a turbine being down in the steady state and not waiting for preparation&lt;sup&gt;b&lt;/sup&gt;</td>
<td>( P_d = \frac{\sum_j h_j \cdot T_{\text{wip},j}}{1 + \sum_j h_j \left( T_{\text{prepare},j} + T_{d,\text{wip},j} \right)} )</td>
</tr>
<tr>
<td>Expected value of steady state downtime due to waiting list&lt;sup&gt;b&lt;/sup&gt;</td>
<td>( E(T_{d,\text{wait},a}) = T_{\text{life}} \cdot \sum_{n=0}^{N_{\text{crew}}} \left( \frac{N_j!}{(N_i - n)!n!} \right) P_d^n \left( 1 - P_d \right)^{N_j - n} )</td>
</tr>
<tr>
<td>Estimated number of operational turbines during the steady state&lt;sup&gt;b&lt;/sup&gt;</td>
<td>( N_{t,\text{st}} = N_t - \sum_j \left( E(T_{d,\text{prepare},j}) + E(T_{d,\text{wip},j}) \right) + E(T_{d,\text{wait},a}) ) / ( T_{\text{life}} )</td>
</tr>
</tbody>
</table>

Expected downtime of failures of type \( j \) that happen during a storm<sup>b</sup> |

\[
E(T_{d,s,j}) = N_{t,\text{st}} h_j \left( \frac{T_{\text{storm}}}{\sum h_k} + e^{-T_{\text{storm}} \sum h_k} \left( \sum h_k \right)^2 \right) - 1
\]
Expected value of number of failures of type $j$, after storm $^b$

$$E\left( N_{f,s,j} \right) = N_{t,st} h_j \left( 1 - e^{-T_{storm} \sum h_k} \right)$$

Number of turbines with failures of type $j$ at start of repair batch $^p$

$$N_{t,d,i,j} = E\left( N_{f,s,j} \right) \text{ for } i = 1$$

Duration of batch $i$ to repair all failures of type $^p$

$$T_{b,i} = \frac{N_{t,d,i,j} \cdot T_{wp,j}}{N_{crew}}$$

Downtime of turbines that fail during this batch $^b$

$$T_{d,f,i,j} = \left( N_{t,st} - N_{t,d,i,j} \right) \left( T_{b,i} + \frac{e^{-T_{b,i} \sum h_k} - 1}{\sum h_k} \right)$$

Downtime of previously failed turbines that are waiting to be repaired in the catch-up period (excluding downtime due to preparation time) $^b$

$$T_{d,w,i,j} = T_{wp,j} \cdot \left( N_b + 1 \right) \left( N_{t,d,i,j} - N_{crew} \frac{N_{b,i}}{2} \right)$$

with: \( N_{b,i} = ROUNDDOWN \left( \frac{N_{t,d,i,j}}{N_{crew}} \right) \) when failures of type $j$ are repaired in this batch, and otherwise:

$$T_{d,w,i,j} = N_{t,d,i,j} \cdot T_{b,i}$$

Expected value of failures during repair batch $^p$

$$E\left( N_{f,i,j} \right) = \frac{\left( N_{t,st} - \sum_{j} N_{t,d,i,j} \right) h_j}{\sum h_k} \left( 1 - e^{-T_{b,i} \sum h_k} \right)$$

Number of turbines with failures of type $j$ at start of repair batch $^p$

$$N_{t,d,i,j} = N_{t,d,i-1,j} + E\left( N_{f,i-1,j} \right) \text{ for } i > 1$$

Total number of failures of type $j$ during storm and catch-up period $^b$

$$N_{f,s+cu,j} = E\left( N_{f,s,j} \right) + \sum_i E\left( N_{f,i,j} \right)$$

Total downtime due to preparation for failures of type $j$ in catch-up period $^b$

$$T_{d,prepare,s+cu,j} = N_{f,s+cu,j} \cdot T_{prepare,j}$$

Total downtime due to failures of type $j$ during storm and catch-up period $^b$

$$T_{d,s+cu,j} = E\left( T_{d,s,j} \right) + T_{d,prepare,s+cu,j} + \sum_{i=1}^{\infty} \left( T_{d,f,i,j} + T_{d,w,i,j} \right)$$

(Summation stops when contribution to downtime becomes less than 0.1%)

Expected total number of failures of type $j$ in storm and catch-up period $^c$

$$E\left( N_{f,s+cu,j} \right) = \int_0^\infty E\left( N_{f,s+cu,j} \left( T_{storm} \right) \right) \cdot p\left( T_{storm} \right) dT_{storm}$$

Expected total downtime for failures of type $j$ in storm and catch-up period $^c$

$$E\left( T_{d,s+cu,j} \right) = \int_0^\infty E\left( T_{d,s+cu,j} \left( T_{storm} \right) \right) \cdot p\left( T_{storm} \right) dT_{storm}$$

Time of catch-up period per storm $^b$

$$T_{catch up} = \sum_i T_{b,i}$$

Total steady state time $^b$

$$T_{st} = (1 - f_s) T_{life} - N_{storms} T_{catch up}$$
<table>
<thead>
<tr>
<th>Aspect</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected value of steady state total number of failures of type (j^b)</td>
<td>[ E\left(N_{f,\text{st},j}\right) = N_j \frac{h_j T_{\text{st}}}{1 + \sum_l h_l \left(T_{\text{prepare},l} + T_{\text{wip},l}\right)} ]</td>
</tr>
<tr>
<td>Average work in progress time for lifting activities</td>
<td>[ T_{\text{wip,\text{lift}}} = \frac{\sum_j h_j T_{\text{wip},j}}{\sum_j h_j} ]</td>
</tr>
<tr>
<td>Probability of mobilising hoisting equipment for (n) repairs</td>
<td>[ P_{\text{mob},n} = \frac{p\left(n-1, T_{i,\text{st}}, N_{\text{i,\text{st}}}, \cdots, N_{\text{i,\text{cu}}}, T_{\text{i}}, T_{n-1}\right) + p'(n-1, \max(T_{i}, T_{n-1}), N_{\text{i,\text{st}}})}{2} ] with: [ T_{n} = T_{\text{mc}} + T_{\text{m}} + n T_{\text{wip,\text{lift}}} ] and [ p(m, T, N) = \frac{N!}{(N - m)!m!} \left(1 - e^{-\sum_j h_j T_{\text{wip},j}}\right)^m \left(1 - e^{-\sum_j h_j T_{\text{wip},j}}\right)^{N-m} ] [ p'(m, T, N) = \frac{N!}{(N - m)!m!} \left(\sum_j h_j \cdot (T - T_{i})\right)^m \left(1 - e^{-\sum_j h_j T_{\text{wip},j}}\right)^{N-m} ]</td>
</tr>
<tr>
<td>Total number of failures that require lifting equipment (b)</td>
<td>[ N_{f,\text{total,\text{lift}}} = E\left(N_{f,\text{st},j}\right) + N_{\text{storms}} \cdot E\left(N_{f,\text{s+cu},j}\right) ]</td>
</tr>
<tr>
<td>Expected number of mobilisations of lifting equipment for (n) repairs (b)</td>
<td>[ E\left(N_{n}\right) = \sum_{n=1}^{\infty} n \cdot P_{\text{mob},n} \cdot E\left(N_{n}\right) ]</td>
</tr>
<tr>
<td>Downtime due to waiting for lifting equipment (b)</td>
<td>[ T_{\text{d,\text{lift}}} = \sum_{n=1}^{\infty} T_{\text{d,\text{lift},n}} \cdot E\left(N_{n}\right), \text{ with:} ] [ T_{\text{d,\text{lift},n}} = (T_{\text{mc}} + T_{\text{m}}) + \frac{1}{2} (T_{\text{mc}} + T_{\text{m}} - T_{\text{wip,\text{lift}}}) (n - 1) ] [ + \frac{1}{2} T_{\text{wip,\text{lift}}} \left(\frac{n(n+1)}{2} - 1\right) ] (Summation stops at (n = \min\left(N_{i}, 100\right)))</td>
</tr>
<tr>
<td>Time to perform preventive maintenance once (b)</td>
<td>[ T_{\text{wip,pm}} = \frac{T_{\text{day}} \cdot T_{\text{pm}} + T_{\text{pm}}}{N_s \cdot n_{\text{crew}} \cdot \left(T_{\text{shift}} - 2 \left(T_{\text{pm}} + T_{\text{pm}}\right)\right)} ]</td>
</tr>
<tr>
<td>Total number of preventive maintenance actions during the lifetime</td>
<td>[ N_{\text{pm}} = N_j \frac{T_{\text{life}}}{T_{\text{pm}}} ]</td>
</tr>
<tr>
<td>Time needed to perform all preventive maintenance</td>
<td>[ T_{\text{pm,\text{total}}} = N_{\text{pm}} \cdot T_{\text{wip,pm}} ]</td>
</tr>
<tr>
<td>Aspect</td>
<td>Model</td>
</tr>
<tr>
<td>----------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------</td>
</tr>
<tr>
<td>Condition that needs to be met in order to have enough crew for preventive maintenance (b)</td>
<td>( T_{\text{pm,total}} \leq N_{\text{crew}} \cdot T_{\text{st}} - \sum_j E\left(N_{\text{f, st},j}\right) \cdot T_{\text{wip},j} )</td>
</tr>
<tr>
<td>Downtime during preventive maintenance (b)</td>
<td>( T_{d,\text{pm}} = N_{\text{pm}} \cdot T_{\text{pm}} )</td>
</tr>
<tr>
<td>Total number of failures of type (j) (b)</td>
<td>( N_{f,\text{total},j} = E\left(N_{f,\text{st},j}\right) + N_{\text{storms}} \cdot E\left(N_{f,\text{st}+\text{cu},j}\right) )</td>
</tr>
<tr>
<td>Total downtime assigned to failures of type (j) (b)</td>
<td>( T_{d,\text{total},j} = E\left(T_{d,\text{prepare},j}\right) + E\left(T_{d,\text{wip},j}\right) + N_{\text{storms}} \cdot E\left(T_{d,\text{st}+\text{cu},j}\right) )</td>
</tr>
<tr>
<td>Total downtime (b)</td>
<td>( T_{d,\text{total}} = E\left(T_{d,\text{wait},\text{in}}\right) + T_{d,\text{lift}} + T_{d,\text{pm}} + \sum_j E\left(T_{d,\text{total},j}\right) )</td>
</tr>
<tr>
<td>Availability (definition)</td>
<td>( \eta_{\text{availability}} = 1 - \frac{T_{d,\text{total}}}{N_{\text{t}} \cdot T_{\text{life}}} )</td>
</tr>
<tr>
<td>Number of vessels (b)</td>
<td>( N_{\text{vessels}} = \text{ROUNDUP}\left(\frac{N_{\text{p}} \cdot N_{\text{crew}}}{N_{\text{passengers}}}\right) )</td>
</tr>
<tr>
<td>Total time of access vessel rental per year (b)</td>
<td>( T_{\text{vessel}} = \frac{N_{\text{pm}} \cdot T_{\text{pm}} + \sum_j N_{f,\text{total},j} \left(T_{\text{diagnose},j} + T_{\text{fix},j}\right)}{\eta_{\text{crew}} \left(T_{\text{shift}} - 2\left(T_{\text{t,to}} + T_{\text{t,in}}\right)\right) \cdot \frac{N_{\text{crew}}}{N_{\text{vessels}}} \cdot T_{\text{shift}}} \cdot T_{\text{life}} )</td>
</tr>
<tr>
<td>Total time that lifting equipment is in the farm per year (b)</td>
<td>( T_{\text{lift}} = \frac{T_{\text{wip, lift}}}{T_{\text{life}}} \cdot \sum_{j,\text{lifting}} N_{f,\text{total},j} )</td>
</tr>
</tbody>
</table>

\(a\) model assumed for this thesis
\(b\) derived from basic models, data or first principles for this thesis
\(c\) Integration to be performed numerically. Currently the expected value for the average storm length, \(E\left(T_{\text{storm}}\right)\), is used without integration.
Appendix E Input data for Horns Rev 1, BOW and OWEZ

This appendix provides input data for the tool as used in Chapters 5 and 6, where the tool is appraised and the theory is validated. Table E-1 through Table E-5 show the data concerning respectively: Size of the wind farms, site conditions, rotor-nacelle assembly, power and thrust curves and failures.

Table E-1 Sizes of the wind farms

<table>
<thead>
<tr>
<th></th>
<th>Horns Rev</th>
<th>Barrow(^{a})</th>
<th>OWEZ(^{b, f, 4})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of turbines in row</td>
<td>8</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>Number of turbines in column</td>
<td>10</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

\(^{a}\) There are actually two lines of 7 and two of 8 turbines.

\(^{b}\) There is actually one row of 12 turbines, one of 9, one of 8 and one of 7

Table E-2 Input data for the site conditions at Horns Rev, BOW and OWEZ

<table>
<thead>
<tr>
<th></th>
<th>Horns Rev</th>
<th>BOW</th>
<th>OWEZ</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wind climate</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weibull scale factor [m/s]</td>
<td>10.83 (^{a})</td>
<td>10.16 (^{b})</td>
<td>9.6 (^{c})</td>
</tr>
<tr>
<td>Weibull shape factor [-]</td>
<td>2.35 (^{a})</td>
<td>2.3 (^{d})</td>
<td>2.31 (^{74})</td>
</tr>
<tr>
<td>Reference height above MSL [m]</td>
<td>62 (^{a})</td>
<td>75 (^{b})</td>
<td>70 (^{c})</td>
</tr>
<tr>
<td>Wind shear power exponent (alpha) [-]</td>
<td>0.1 (^{e})</td>
<td>0.1 (^{220, 263})</td>
<td>0.1 (^{f})</td>
</tr>
</tbody>
</table>

|                       |           |     |      |
| **Water levels**      |           |     |      |
| Water depth (deepest in site) [m] | 13.5 \(^{90}\) | 20 \(^{90, 257}\) | 18 \(^{1, 91, 106, 30}\) |
| Highest astronomical tide above MSL [m] | 0.8 \(^{253}\) | 4.5 \(^{90, 257}\) | 0.8 \(^{106}\) |
| Lowest astronomical tide (negative value) [m] | -0.8 \(^{253}\) | -4.5 \(^{90, 257}\) | -0.8 \(^{106}\) |
| Positive storm surge [m] | 2.5 \(^{257}\) | 2.5 \(^{f}\) | 2.5 \(^{f}\) |
| Negative storm surge (negative value) [m] | -0.5 \(^{h}\) | -0.5 \(^{f}\) | -0.5 \(^{f}\) |

|                       |           |     |      |
| **Wave and current climate** |           |     |      |
| Significant wave height (1 year extreme) [m] | 3.3 \(^{i}\) | 5.65 \(^{j}\) | 5.65 \(^{112}\) |
| Significant wave height (50 year extreme) [m] | 5 \(^{k}\) | 6.29 \(^{j}\) | 6.29 \(^{112, 189}\) |
| Depth average current (50 year extreme) [m/s] | 0.8 \(^{m}\) | 0.8 \(^{f}\) | 0.8 \(^{f}\) |
| Angle between wave and current (50 year extreme) [degrees] | 20 \(^{n}\) | 20 \(^{f}\) | 20 \(^{f}\) |

|                       |           |     |      |
| **Water properties**   |           |     |      |
| Average density [kg/m\(^3\)] | 1025 \(^{d}\) | 1025 \(^{f}\) | 1025 \(^{f}\) |
| Maximum temperature at seabed level [°C] | 15 \(^{149}\) | 15 \(^{f}\) | 15 \(^{f}\) |
### Geophysical properties

<table>
<thead>
<tr>
<th></th>
<th>Horns Rev Value</th>
<th>Source</th>
<th>BOW Value</th>
<th>Source</th>
<th>OWEZ Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seabed grain size ($d_{50}$) [m]</td>
<td>0.0002</td>
<td></td>
<td>0.0002</td>
<td>(f)</td>
<td>0.0002</td>
<td>(f)</td>
</tr>
<tr>
<td>Seabed grain size ($d_{90}$) [m]</td>
<td>0.0005</td>
<td></td>
<td>0.0005</td>
<td>(f)</td>
<td>0.0005</td>
<td>(f)</td>
</tr>
<tr>
<td>Typical soil friction angle [degrees]</td>
<td>35</td>
<td>(p)</td>
<td>30</td>
<td>(q)</td>
<td>35</td>
<td>(f)</td>
</tr>
<tr>
<td>Typical submerged unit weight [N/m$^3$]</td>
<td>10,000</td>
<td>(p)</td>
<td>10,000</td>
<td>(f)</td>
<td>10,000</td>
<td>(f)</td>
</tr>
</tbody>
</table>

### Accessibility information

<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance to harbour (for maintenance) [m]</td>
<td>20000</td>
<td>(190)</td>
<td>15000</td>
<td>(92)</td>
<td>15000</td>
<td>(s)</td>
</tr>
<tr>
<td>Reference significant wave height limit [m]</td>
<td>1.5</td>
<td>(283)</td>
<td>1.5</td>
<td>(91)</td>
<td>1.5</td>
<td>(f)</td>
</tr>
<tr>
<td>Fraction of time with no access for reference wave height [-]</td>
<td>0.6</td>
<td>(190, 283)</td>
<td>0.51</td>
<td>(91)</td>
<td>0.6</td>
<td>(f)</td>
</tr>
<tr>
<td>Weibull scale factor for no access windows [h]</td>
<td>19.5</td>
<td>(t)</td>
<td>19.5</td>
<td>(f)</td>
<td>19.5</td>
<td>(f)</td>
</tr>
<tr>
<td>Weibull shape factor for no access windows [-]</td>
<td>0.65</td>
<td>(t)</td>
<td>0.65</td>
<td>(f)</td>
<td>0.65</td>
<td>(f)</td>
</tr>
</tbody>
</table>

### Grid coupling point

<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance to grid coupling point [m]</td>
<td>55,000</td>
<td>(u)</td>
<td>30,300</td>
<td>(u)</td>
<td>15,000</td>
<td>(u)</td>
</tr>
<tr>
<td>Frequency [Hz]</td>
<td>50</td>
<td>(65)</td>
<td>50</td>
<td>(u)</td>
<td>50</td>
<td>(u)</td>
</tr>
<tr>
<td>Voltage [V]</td>
<td>169,000</td>
<td>(65)</td>
<td>400,000</td>
<td>(221, 311)</td>
<td>50</td>
<td>150,000</td>
</tr>
</tbody>
</table>

---

*a* Weibull function fitted through data for wind speed bins in four directions.

*b* 9 m/s average wind speed at 75 m height translated to scale factor.

*c* 8.5 m/s average wind speed at 70 m height translated to scale factor.

*d* Typical value, not specific for this site.

*e* Approximate fit to several wind speed data series as a function of height.

*f* Assumed to be the same as at Horns Rev.

*g* Reported tidal range increased slightly to estimate extreme value and divided in equal positive and negative amplitude.

*h* Guess.

*i* 6 m wave height that is exceeded every year divided by 1.86 to estimate significant wave height.

*j* Assumed to be the same as at OWEZ (which has a more similar water depth than Horns Rev).

*k* Extreme significant wave height with one year return period is approximately 0.64 times that with a 50 year return period. A scatter diagram, probably measured over much less than 50 years, reports a maximum observed significant wave height ($H_{m0}$) of about 4.3 m.

*l* Values of different sources are not consistent. The extreme wave height with 100 year return period reported in one source is divided by 1.86 as an estimate of the significant wave height.

*m* The source doesn’t mention the return period for this value for the currents during storms, nor whether it is a depth averaged value.

*n* Arbitrary value.
Temperature variation with height subtracted from highest surface temperature, achieved in August.

P Depth averaged value from reported friction angle profile. Lighter layer at greater depth ignored.

Q Because sand and hard clay is reported for this sight, a slightly lower friction angle is assumed than at Horns Rev, which is mostly sand.

R Estimated from maps and reference distances.

S Five kilometre added to the minimum distance to shore of 10 km, because the nearest harbour is further south.

T Values for the location ‘IJmuiden minutiestortplaats’ and not for Horns Rev.

V There is also a 132kV connection at this location.

<table>
<thead>
<tr>
<th>Table E-3 Input data for the rotor-nacelle assemblies</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Geometric properties</strong></td>
</tr>
<tr>
<td>Rotor radius [m]</td>
</tr>
<tr>
<td>Rotor solidity [-]</td>
</tr>
<tr>
<td>Front area nacelle [m²]</td>
</tr>
<tr>
<td>Height from yaw to hub [m]</td>
</tr>
<tr>
<td>Yaw bearing (outer) diameter [m]</td>
</tr>
<tr>
<td><strong>Mass properties</strong></td>
</tr>
<tr>
<td>Mass of rotor and nacelle [kg]</td>
</tr>
<tr>
<td>Eccentricity (downwind is positive) [m]</td>
</tr>
<tr>
<td><strong>Aerodynamic load properties</strong></td>
</tr>
<tr>
<td>Cd rotor idling in vane [-]</td>
</tr>
<tr>
<td>Cd nacelle [-]</td>
</tr>
<tr>
<td>Maximum operational thrust [N]</td>
</tr>
<tr>
<td>Wind speed at maximum thrust [m/s]</td>
</tr>
<tr>
<td><strong>Electrical properties</strong></td>
</tr>
<tr>
<td>Generator voltage [V]</td>
</tr>
<tr>
<td><strong>Operational properties</strong></td>
</tr>
<tr>
<td>Preventive maintenance interval [h]</td>
</tr>
<tr>
<td>Preventive maintenance duration [h/turbine]</td>
</tr>
<tr>
<td>Preventive maintenance consumables costs [€/service]</td>
</tr>
<tr>
<td>People per maintenance crew [-]</td>
</tr>
<tr>
<td><strong>Financial data</strong></td>
</tr>
<tr>
<td>Purchase price [€]</td>
</tr>
<tr>
<td>One-off warranty premium (percentage of purchase price) [%]</td>
</tr>
</tbody>
</table>

a Based on generic data for similar rotors

b Vestas V80 brochure: Height for transport of 4 m and width 3.4 m; Area rounded up 14 m² to include height including cooler top 5.4 m.

c Height of 4 m and width of 3.85 m.

d Centreline of the hub is assumed to be in the middle of the nacelle of 4 m height.

e Generic value

f Nacelle mass of 79 tonne and three times the blade mass of 6.5 tonne.
Stated references give this total head mass and a nacelle mass of 91 tonne. The V90 brochure\textsuperscript{298} states a nacelle mass of 66 tonne only. The higher value is taken, because these references are specifically for the turbines at BOW.

Guess, based on nacelle length of approximately 10 m.

Generic value, assuming rotor misalignment or failed pitch system.

Generic value.

Maximum thrust determined from thrust coefficient curve multiplied with 1.5 dynamic amplification factor determined from simulations of a 5 MW turbine\textsuperscript{32}. The result is rounded up to the nearest 5000 N, because values are only available at integer wind speeds in m/s.

Wind speed corresponding with the result of the maximum thrust.

Various sources state voltage levels of 480 and 690 V. The higher value is assumed, considering the need of high voltage in the connections to the public grid.

Assumed to be the same as for the V80.

Average of 2 different types of preventive maintenance. For the duration a workable day of 9 hours is assumed.

Costs of the V80 are increased by the ratio of the purchase prices (22/15).

Nine people work in one shift. Three crews of three people are assumed, because a shift has six technicians of the operator and three Vestas service personnel. For preventive maintenance actually only 2 technicians are needed.

An estimate of installation costs is subtracted from data provided for Rødsand and Horns Rev. The result is corrected for inflation to 2012 prices.

Based on purchase price of V80, assuming that the price scales proportional to the mass.

\begin{table}[h]
\centering
\begin{tabular}{lcccccc}
\hline
Maintenance group ID$^{b}$ & MTBF$^{c}$ & Diagnose time$^{d}$ & Repair time$^{e}$ & Lifting equipment needed & Costs of consumables$^{f}$ \\
\hline
Needs lifting & 73,000 & 8 & 85 & Yes & 210,000 & 310,000 \\
Needs diagnosis & 6,100 & 8 & 5 & No & 1,100 & 1,600 \\
No diagnosis & 13,000 & 0 & 5 & No & 1,600 & 2,300 \\
\hline
\end{tabular}
\caption{Failure data for the rotor-nacelle assemblies\textsuperscript{190}}
\end{table}

Original data is obtained for the V80 at Horns Rev. Most data is assumed to be the same for the V90. Waiting time for spare parts is 0 h for all categories.

Division of failures into categories is based on the type of component and the reported repair time.

Determined from the reported failure rates of all failures in the category.

This is not reported and therefore a guess.

Reported repair times of failures in one category are weighted with failure rates.

Reported costs of failures in one category are weighted with failure rates.

Costs of the V80 are increased by the ratio of the purchase prices (22/15).
<table>
<thead>
<tr>
<th>Wind speed [m/s]</th>
<th>Power [kW] V80</th>
<th>Power [kW] V90</th>
<th>Thrust coefficient [-] V80</th>
<th>Thrust coefficient [-] V90</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.9999</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>66.6</td>
<td>77</td>
<td>0.818</td>
<td>0.815</td>
</tr>
<tr>
<td>5</td>
<td>154</td>
<td>190</td>
<td>0.806</td>
<td>0.818</td>
</tr>
<tr>
<td>6</td>
<td>282</td>
<td>353</td>
<td>0.804</td>
<td>0.823</td>
</tr>
<tr>
<td>7</td>
<td>460</td>
<td>581</td>
<td>0.805</td>
<td>0.823</td>
</tr>
<tr>
<td>8</td>
<td>696</td>
<td>886</td>
<td>0.806</td>
<td>0.824</td>
</tr>
<tr>
<td>9</td>
<td>996</td>
<td>1,273</td>
<td>0.807</td>
<td>0.802</td>
</tr>
<tr>
<td>10</td>
<td>1,341</td>
<td>1,710</td>
<td>0.793</td>
<td>0.73</td>
</tr>
<tr>
<td>11</td>
<td>1,661</td>
<td>2,145</td>
<td>0.739</td>
<td>0.648</td>
</tr>
<tr>
<td>12</td>
<td>1,866</td>
<td>2,544</td>
<td>0.709</td>
<td>0.564</td>
</tr>
<tr>
<td>13</td>
<td>1,958</td>
<td>2,837</td>
<td>0.409</td>
<td>0.49</td>
</tr>
<tr>
<td>14</td>
<td>1,988</td>
<td>2,965</td>
<td>0.314</td>
<td>0.39</td>
</tr>
<tr>
<td>15</td>
<td>1,997</td>
<td>2,995</td>
<td>0.249</td>
<td>0.304</td>
</tr>
<tr>
<td>16</td>
<td>1,999</td>
<td>3,000</td>
<td>0.202</td>
<td>0.246</td>
</tr>
<tr>
<td>17</td>
<td>2,000</td>
<td>3,000</td>
<td>0.167</td>
<td>0.203</td>
</tr>
<tr>
<td>18</td>
<td>2,000</td>
<td>3,000</td>
<td>0.14</td>
<td>0.17</td>
</tr>
<tr>
<td>19</td>
<td>2,000</td>
<td>3,000</td>
<td>0.119</td>
<td>0.144</td>
</tr>
<tr>
<td>20</td>
<td>2,000</td>
<td>3,000</td>
<td>0.102</td>
<td>0.124</td>
</tr>
<tr>
<td>21</td>
<td>2,000</td>
<td>3,000</td>
<td>0.088</td>
<td>0.107</td>
</tr>
<tr>
<td>22</td>
<td>2,000</td>
<td>3,000</td>
<td>0.077</td>
<td>0.094</td>
</tr>
<tr>
<td>23</td>
<td>2,000</td>
<td>3,000</td>
<td>0.067</td>
<td>0.082</td>
</tr>
<tr>
<td>24</td>
<td>2,000</td>
<td>3,000</td>
<td>0.06</td>
<td>0.073</td>
</tr>
<tr>
<td>25</td>
<td>2,000</td>
<td>3,000</td>
<td>0.053</td>
<td>0.065</td>
</tr>
<tr>
<td>25.0001</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Appendix F Source for reference data for realised wind farms

Table F-1 provides the sources of the reference data of the realised wind farms Horns Rev, BOW and OWEZ.

<table>
<thead>
<tr>
<th>Table F-1 Sources for reference data for Horns Rev, BOW and OWEZ</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Horns Rev</strong></td>
</tr>
<tr>
<td><strong>Support structure</strong></td>
</tr>
<tr>
<td>Hub height (MSL+) [m]</td>
</tr>
<tr>
<td>Platform height (MSL+) [m]</td>
</tr>
<tr>
<td>Tower base diameter [m]</td>
</tr>
<tr>
<td><strong>Transition piece</strong></td>
</tr>
<tr>
<td>Diameter [m]</td>
</tr>
<tr>
<td>Length [m]</td>
</tr>
<tr>
<td>Overlap [m]</td>
</tr>
<tr>
<td><strong>Pile</strong></td>
</tr>
<tr>
<td>Diameter [m]</td>
</tr>
<tr>
<td>Thickness [mm]</td>
</tr>
<tr>
<td>Length [m]</td>
</tr>
<tr>
<td>Penetration [m]</td>
</tr>
<tr>
<td><strong>Masses [10^3 kg]</strong></td>
</tr>
<tr>
<td>Tower</td>
</tr>
<tr>
<td>Transition piece</td>
</tr>
<tr>
<td>Pile</td>
</tr>
<tr>
<td><strong>Scour protection</strong></td>
</tr>
<tr>
<td>Diameter [m]</td>
</tr>
<tr>
<td>Thickness [m]</td>
</tr>
<tr>
<td><strong>Scour protection – Armour layer</strong></td>
</tr>
<tr>
<td>Grain size [mm]</td>
</tr>
<tr>
<td>Thickness [m]</td>
</tr>
<tr>
<td>Thickness near pile [m]</td>
</tr>
<tr>
<td><strong>Scour protection – Filter layer 1</strong></td>
</tr>
<tr>
<td>Grain size [mm]</td>
</tr>
<tr>
<td>Thickness [m]</td>
</tr>
<tr>
<td><strong>Electrical system</strong></td>
</tr>
<tr>
<td><strong>Transmission</strong></td>
</tr>
<tr>
<td>Burial depth [m]</td>
</tr>
<tr>
<td>Conductor area [mm²]</td>
</tr>
<tr>
<td>Voltage level [kV]</td>
</tr>
<tr>
<td>Onshore shunt reactor power [MVar]</td>
</tr>
<tr>
<td><strong>Infield</strong></td>
</tr>
<tr>
<td>Burial depth [m]</td>
</tr>
<tr>
<td>Conductor area [mm²]</td>
</tr>
<tr>
<td>Voltage level [kV]</td>
</tr>
<tr>
<td><strong>Maintenance</strong></td>
</tr>
<tr>
<td>Shifts per day</td>
</tr>
<tr>
<td>Crews per shift</td>
</tr>
<tr>
<td>Number of access vessels</td>
</tr>
<tr>
<td>Availability [%]</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>------------------</td>
</tr>
<tr>
<td><strong>Layout</strong></td>
</tr>
<tr>
<td>Spacing in column [m]</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Spacing in row [m]</td>
</tr>
<tr>
<td>Array efficiency [%]</td>
</tr>
<tr>
<td><strong>System level parameters</strong></td>
</tr>
<tr>
<td>Annual output [GWh]</td>
</tr>
<tr>
<td>Investment costs [M€]</td>
</tr>
<tr>
<td>LPC [€ct/kWh]</td>
</tr>
<tr>
<td>of which:</td>
</tr>
<tr>
<td>Investment [%]</td>
</tr>
<tr>
<td>O&amp;M [%]</td>
</tr>
<tr>
<td>Balancing [%]</td>
</tr>
</tbody>
</table>
Appendix G Redesign of V80 with variation of rotor diameter

Power curve
To scale the power curve, it is assumed that the maximum power coefficient of the reference rotor can also be achieved for the new rotor diameters. Considering that power is proportional to the square of the rotor diameter and the cube of the wind speed, the power curve is adjusted by scaling the wind speed axis according to:

\[ V_{\text{new}} = V_{\text{ref}} \left( \frac{D_{\text{rotor, new}}}{D_{\text{rotor, ref}}} \right)^{\frac{2}{3}} \]  

(G-1)

with:

- \( V_{\text{new}} \) = wind speed for new power curve,
- \( V_{\text{ref}} \) = wind speed for power curve of V80,
- \( D_{\text{rotor, new}} \) = rotor diameter of new rotor-nacelle assembly design,
- \( D_{\text{rotor, ref}} \) = rotor diameter of V80.

By scaling the wind speed, rather than the power for wind speeds below rated, the shape of the curve in the transition from partial load to full load is maintained. The cut-in and cut-out wind speeds are kept the same.

Thrust curve
The scaling of the power curve was done under the assumption that the power coefficient is not changed. This applies to partial load as well as full load operation, so a point on the reference power curve and its associated point on the scaled curve correspond with operational conditions that have the same power coefficient. It is reasonable to assume that these operational points therefore also have the same induction factor and thus the same thrust coefficient. Thus, the scaling of the wind speed axis that is applied to the power curve is also applied to the thrust coefficient curve.

RNA mass and mass eccentricity
To scale the blade mass, it is assumed that the tip deflection or maximum stress at rated wind speed is the design driver. The scaling rules applied to the power curve and the thrust curve imply that the thrust coefficient at rated wind speed is the same for the reference turbine and the redesigned turbine. Furthermore, it is assumed that the effective modulus of elasticity at each relative spanwise position remains unchanged. Table G-1 shows the scaling rules for several parameters, assuming that chord scales linearly with rotor diameter.
Table G-1 Scaling rules for several parameters when chord scales linearly with rotor diameter and when either tip deflection or maximum stress is the design driver

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Primary scaling rule</th>
<th>Expressed in ( D_{\text{rotor}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flapping moment, ( M )</strong></td>
<td>( D_{\text{rotor}}^3 V^2 )</td>
<td>( D_{\text{rotor}}^{5/3} )</td>
</tr>
<tr>
<td><strong>When tip deflection is design driver</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tip deflection</td>
<td>( D_{\text{rotor}}^2 M / I )</td>
<td>(Unchanged)</td>
</tr>
<tr>
<td>Moment of inertia, ( I )</td>
<td>( t D_{\text{rotor}}^3 = D_{\text{rotor}}^2 M / D_{\text{rotor}} )</td>
<td>( D_{\text{rotor}}^{11/3} )</td>
</tr>
<tr>
<td>Wall thickness, ( t )</td>
<td>( t D_{\text{rotor}}^2 = D_{\text{rotor}}^2 M / D_{\text{rotor}} )</td>
<td>( D_{\text{rotor}}^{2/3} )</td>
</tr>
<tr>
<td>Blade mass</td>
<td>( t D_{\text{rotor}}^2 = D_{\text{rotor}}^2 M / D_{\text{rotor}} )</td>
<td>( D_{\text{rotor}}^{11/3} )</td>
</tr>
<tr>
<td><strong>When maximum stress is design driver</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum stress</td>
<td>( D_{\text{rotor}} M / I )</td>
<td>(Unchanged)</td>
</tr>
<tr>
<td>Moment of inertia, ( I )</td>
<td>( t D_{\text{rotor}}^3 = D_{\text{rotor}}^2 M / D_{\text{rotor}} )</td>
<td>( D_{\text{rotor}}^{11/3} )</td>
</tr>
<tr>
<td>Wall thickness, ( t )</td>
<td>( t D_{\text{rotor}}^2 = D_{\text{rotor}}^2 M / D_{\text{rotor}} )</td>
<td>( D_{\text{rotor}}^{2/3} )</td>
</tr>
<tr>
<td>Blade mass</td>
<td>( t D_{\text{rotor}}^2 = D_{\text{rotor}}^2 M / D_{\text{rotor}} )</td>
<td>( D_{\text{rotor}}^{11/3} )</td>
</tr>
</tbody>
</table>

For rotor diameters of multi-MegaWatt turbines the tip deflection is often the design driver. However, the blade can be re-optimised for instance by the selection of thicker aerofoils for larger blades. Furthermore, when tip deflection is the design driver, it may have less effect on the redesign of outboard sections than of inboard sections. Therefore, mass of the blades is assumed to scale with \( D^2 \). This scaling only applies to the 19.5 tonnes blade mass and not to the rest of the mass of the RNA.

The original mass eccentricity corresponds with an assumed eccentricity of rotor mass of -6.05 meter and an eccentricity of the rest of the RNA mass of -1 meter. With these eccentricities and the scaling of rotor mass as given above, the eccentricity of the RNA, \( d_{\text{ecc}} \), becomes:

\[
d_{\text{ecc}} = -\frac{m_{\text{rotor}} \left( \frac{D_{\text{rotor, new}}}{D_{\text{rotor, ref}}} \right)^2 - 6.05 + m_{\text{nacelle}}}{m_{\text{rotor}} \left( \frac{D_{\text{rotor, new}}}{D_{\text{rotor, ref}}} \right)^2 + m_{\text{nacelle}}} \quad (G-2)
\]

with:

\[m_{\text{rotor}} = \text{mass of the rotor,}\]
\[m_{\text{nacelle}} = \text{mass of the nacelle.}\]

**Maximal operational thrust and corresponding wind speed**

The wind speed at which maximum operational thrust occurs is assumed to scale in the same way as in the scaling of the power curve and thrust curve. Since the thrust coefficient then remains the same, the maximum operational thrust scales with \( D_{\text{rotor}}^2 \) and \( V^2 \). Substituting the scaling for the wind speed leads to a maximum thrust, \( T_{\text{new}} \), of:
RNA purchase price

The scaling of the purchase price is crucial for the optimisation, but it is expected to be imprecise due to limited information. The blade costs will change due to its changed design, but also the design and costs of other components may change. For instance, the torque in the drive train will change and this affects the gearbox design. For several other components the aerodynamic moments and moments due to gravity loads are design drivers. The following scaling rules are derived for these loads at rated wind speed:

- torque scales with $D_{rotor}^{5/3}$
- aerodynamic moment scales with $D_{rotor}^{5/3}$
- moment due to gravity scales with $D_{rotor}^{8/3}$

Gearbox costs are nearly linearly proportional to torque. When the maximum stress is the design driver, it is shown in Table G-1 that the blade mass scales the same as the flapping moment. For other components the mass is also assumed to scale proportional to the scaling of the moments that drive their design. However, it is not known whether the aerodynamic moment or the moment due to gravity is dominant. Therefore, the mass of these components is assumed to scale with $D^2$, as an intermediate proportionality. Not the entire mass and the entire costs of these components are expected to scale with the rotor diameter. A fraction of the mass and costs of these components is assumed to remain the same as that of the reference RNA.

Table G-2 gives an estimate of which cost contributions are affected by a change in rotor diameter, grouped according to the expected scaling. The percentage of the component costs in the reference RNA purchase price is based on the cost breakdown given by EWEA. Based on Table G-2 the costs of the RNA, $C_{RNA,new}$, are modeled by:

$$C_{RNA,new} = \left(0.28 + 0.22 \left( \frac{D_{rotor,new}}{D_{rotor,ref}} \right)^{5/3} \right) + \left(0.50 \left( f_{fixed} + \left( f_{fixed} - 1 \right) \left( \frac{D_{rotor,new}}{D_{rotor,ref}} \right)^2 \right) \right) C_{RNA,ref}$$

with:

$$f_{fixed} = \text{fraction of costs of components with mass scaling assumed to remain the same.}$$

Initially, 10% of the costs of components with mass scaling are assumed to be fixed.
Table G-2 Contributions of RNA components to purchase price, grouped according to assumed scaling with rotor diameter (percentages according to EWEA$^{107}$)

<table>
<thead>
<tr>
<th>Component</th>
<th>Fraction of RNA purchase price [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scaling with $D_{\text{rotor}}^2$</strong></td>
<td></td>
</tr>
<tr>
<td>Blades</td>
<td>38.0%</td>
</tr>
<tr>
<td>Hub</td>
<td>2.3%</td>
</tr>
<tr>
<td>Bearings</td>
<td>2.1%</td>
</tr>
<tr>
<td>Main shaft</td>
<td>3.3%</td>
</tr>
<tr>
<td>Main frame</td>
<td>4.8%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>50.4%</td>
</tr>
<tr>
<td><strong>Scaling with $D_{\text{rotor}}^{5/3}$</strong></td>
<td></td>
</tr>
<tr>
<td>Gearbox</td>
<td>22.1%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>22.1%</td>
</tr>
<tr>
<td><strong>Independent of rotor diameter</strong></td>
<td></td>
</tr>
<tr>
<td>Generator</td>
<td>5.9%</td>
</tr>
<tr>
<td>Yaw system</td>
<td>2.1%</td>
</tr>
<tr>
<td>Pitch system</td>
<td>4.5%</td>
</tr>
<tr>
<td>Power converter</td>
<td>8.6%</td>
</tr>
<tr>
<td>Brake system</td>
<td>2.3%</td>
</tr>
<tr>
<td>Nacelle housing</td>
<td>2.3%</td>
</tr>
<tr>
<td>Screws</td>
<td>1.8%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>27.5%</td>
</tr>
</tbody>
</table>

**Other input parameters**
Other design variables and properties of the RNA, such as its reliability, are assumed to remain unchanged.
Appendix H Closed questions of the questionnaire

The closed questions of the questionnaire consist of statements for which the respondent can indicate agreement on the following scale:

1. I strongly disagree
2. I disagree
3. I disagree somewhat
4. I neither agree nor disagree
5. I agree somewhat
6. I agree
7. I strongly agree

The full statements in the questionnaire are, in the same order as in Figure 6-8:

- I don’t think that I would ever use a tool like this, even if it were improved
- This prototype would already be a valuable contribution to our design process as it is
- I couldn’t optimise the turbine design with this tool, because changing turbine data had too little effect on the results
- The results of the tool showed me directions to improve the turbine design that I would like to explore further
- I think I could use results of the tool to convince our customers of the superiority of the final design
- I recognise use case 1 as useful contributions to our design process
- I recognise use case 2 as useful contributions to our design process
- I recognise use case 3 as useful contributions to our design process
- I recognise use case 4 as useful contributions to our design process
- The outcome of the design using the tool is better than the one I would have made without the tool
- The tool gave me the opportunity to optimise parameters that would otherwise be fixed very early in the design process
- The tool gave me useful quantitative data where I would otherwise have used qualitative information
- The tool gave me quantitative data with a higher precision than I would otherwise have had
- This tool saved me time with respect to the methods that I would otherwise have used to achieve the results of this test program
- Using this tool I needed less colleagues than I would otherwise have used to get the results of this test program
- Using this tool I needed less external consultants than I would otherwise have used to get the results of this test program
- I think I could use results of the tool to better assess the competitive position and pricing of the final product
- The tool provided me better insight in the customer needs
- I found it difficult to make design decisions, because I suspected too large uncertainty in the results
- I have confidence in the economic results of the tool, considering its purpose in the test program
- I have confidence in the technical results of the tool, considering its purpose in the test program
- The tool provided unexpected results that made me doubt its validity
- Variation of turbine data gave results that contradicted my earlier experience
- I have little confidence in the outcome of the use cases, because the tool is implemented for a single (wind farm) concept only
- I missed turbine parameters in the input data of which I expect influence on farm design and performance that is larger than that of the used parameters
- I’m comfortable with the fact that the tool operates in a field with which I’m less familiar
- I could not generate reasonable estimates of the required input data to properly assess the tool
- The time I had available to get experience with the tool was undesirably short because the tool took much computation time
- The time I had available to get experience with the tool was undesirably short because it took me much time to operate the tool (excluding time to prepare the input data)
- The time I had available to get experience with the tool was undesirably short because it took me much time to learn working with the tool
- The tool let me down very often (aborted optimisations, hang-ups, error messages, …)
- The user interface caused me too much inconvenience to focus on the test program
- The time I had available to get experience with the tool was undesirably short because of reasons that do not concern the test program
Curriculum vitae

Michiel Bastiaan Zaaijer was born on 17 July 1969 in Chingola, Zambia. He attended pre-university education at Maurick College in Vught, obtaining his diploma in 1987. He studied applied physics at Delft University of Technology and earned his degree ‘ingenieur’ (MSc) in 1993.

After his graduation Michiel joined the navigation group of Delft University's Electrical Engineering department to work as a researcher in the field of radio navigation. Subjects of his research at the navigation group included the application of GPS and MLS for approach and landing of aircraft. During this work he prepared and executed flight trials in the Netherlands and in the UK.

In June 1999 Michiel joined the wind energy community. He researched various aspects of offshore wind farms, such as: support structures and loading, foundations and dynamics, operation and maintenance, life cycle costs of electricity and nacelle layouts. His research is performed in contribution to projects for the European Commission and the Dutch Government, amongst which: DOWEC, OWTES and Icorass. He was involved in the initiation of projects and contributed to proposals and management of WE@Sea, PhD@Sea, Upwind, Innwind and FLOW. Since April 2013 he is appointed scientific director of the Top consortium Knowledge and Innovation ‘Wind op Zee’.

Michiel made and taught various courses, such as ‘Introduction to wind energy’, ‘Offshore wind farm design’ and ‘Wind turbine design’. He also coordinates the industry course ‘Technology of offshore wind energy’. He also supervised many student projects and several PhD researchers. He currently continues his work as assistant professor at Delft University.

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Michiel Zaaijer

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