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Vattenfall Optimizes Offshore Wind Farm Design

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Abstract

In this paper we describe the usage of operations research for offshore wind farm design in Vattenfall, one of the world's leading European companies for Offshore Wind Energy.

We focus on two key aspects of the wind farm design process Vattenfall faces: deciding where to locate the turbines and how to interconnect them with cables. The first task is important as the placement of each turbine creates an interference on the neighbouring turbines, causing a power loss at the overall farm level. The optimizers need to minimize this interference according to the wind conditions, while also considering the other costs involved, depending on, e.g., the water depth or soil conditions at each position. The second tasks, i.e. the cable optimization, considers both immediate costs and long-term costs connected with the electrical infrastructure.

We developed mixed integer programming models as well as matheuristic techniques to solve the two problems as they arise in practical applications.

The resulting tools have enabled a competitive advantage for Vattenfall at different levels: they facilitate increased revenues and reduced costs (in the order of 10 million Euros of Net Present Value per farm), while ensuring a much faster, more streamlined and efficient design process. Considering only the sites already acquired using our optimization tools, we experienced NPV gains of more than 150 M Euros. This has contributed substantially to the competitiveness of Vattenfall in offshore tenders, and made green energy cheaper for the end customers. The tools have also been used to design, among others, the first wind farm that will be constructed subsidy free.

Keywords: Offshore wind energy, Operations Research, Analytics, Wind farm layout, Sustainability.

Introduction

If you have been lucky to fly in clear weather over the ocean, you may have passed over an offshore wind farm and admired the turbines all neatly arranged in long straight rows, symmetric from all angles. However, lining up turbines often results in poor performances. This is because when wind hits one turbine, its flow may be hindered from hitting a downwind turbine as forcefully as it would without the interference. Turbines disrupting wind flow are referred to as casting *wind shadows* on other turbines in the farm, resulting in lower production. A smart placement of turbines reduces this *wake effect*. Consequently, in contrast to the elegant straight rows of turbines, in the future, you will see a new kind of beauty - drawn by math and optimised in production. This is where this project brought Vattenfall, and this paper is the story of the journey.

Vattenfall is a one of Europe's largest producers and retailers of electricity and heat. Its main markets are Sweden, Germany, the Netherlands, Denmark, and the UK. The Group has approximately 20,000 employees. The Parent Company, Vattenfall AB, is 100% owned by the Swedish state

For more than 100 years Vattenfall has electrified industries, supplied energy to people's homes and modernised energy use through innovation and cooperation. Vattenfall is the 2nd largest offshore wind power developer in the world with an annual investment budget for wind farms of about 1.5 billion euros, with major offshore wind farms in operation and under development.

Our project was developed within the Vattenfall Wind division. The business of Vattenfall Wind consists in constructing wind farms and selling the energy produced. This is a valuable business as the demand for green energy is increasing in Europe and each project has potential for a high return of investment. However, this is also a challenging business: the construction of wind farms in Europe is mainly based on an auction system. Only the winner of the auction has the right to construct the farm and receives all the revenues from selling the energy during the farm’s lifetime (typically 25-30 years). Thus, it is essential for Vattenfall to be able to place a competitive bid while still ensuring a profitable business. In principle, this means minimizing construction and lifetime costs while maximizing production/revenue.

Being a winner-take-all market, it is important for Vattenfall to have a competitive advantage in these auctions. For this reason, Vattenfall looked into operations research (OR) methods to increase revenue and reduce costs. To this end, Vattenfall collaborated with Technical University of Denmark and University of Padova (and, later, University of Bologna). More specifically, in this project we focused on the design phase of offshore wind farms. Designing a wind farm is a complex and multi-disciplinary project, involving different expertises and many tasks. Most of the main optimization tasks of the problem were traditionally handled manually. This is where OR and analytics expertise made the difference: we developed comprehensive tools to generate efficient wind farm layouts and to support the experts in the field. In particular, we determine the optimal locations of turbines and the cable routing used to connect them to substation(s) that collect the energy offshore for distribution onshore.

In this paper we provide an overview of our work, focusing on its impact in practice. We first explain the offshore market structure in Europe and describe the main limitations and goals in our optimization. We then describe the two primary optimization problems our project focuses on—turbine location and cable routing—showing practical examples of application. We will illustrate the story of the project and the challenges we encountered in its development and establishment in Vattenfall. Finally, we will summarize the impact of using OR and analytics in offshore wind farm design, and briefly comment on possible future directions.

The paper will provides only an overview of the methods used to solve these complex optimization tasks; for more details about the methods the reader is referred to (Fischetti 2014, 2018), (Fischetti et al. 2015), (Fischetti and Monaci 2016), and (Fischetti and Pisinger 2017, 2019).

Wind farm auctions: a winner-take-all business

In their strategic energy infrastructure planning, each country in Europe decides to construct energy capacity according to the expected demand. In this overall country strategy, some energy capacity is assigned to offshore wind plants. To get these plants constructed, the State typically offers an area at auction: the company that can establish the plant requiring the lowest subsidies wins the auction and the rights to construct and operate the farm in that area. Therefore, only the company with the lowest bid gets to capitalize their investment and is allowed to sell the energy to the country during the farm’s lifetime. It is therefore important for companies like Vattenfall to be realistic in these bids and find innovative ways to win the competition while still making a profit. Our project allows this by increasing power production over the farm lifetime at even lower construction costs.

To better understand our contribution, we need to put things into context. In this section, we provide some main concepts on the tender process, to clarify the considerations we have in our optimization tasks.

The State in many cases decides a certain target supply for wind energy and selects a certain area where it wants the wind farm to be constructed. The first (left) plot in Figure 1. shows, for example, the available area for Danish Kriegers Flak, an offshore wind farm in Denmark recently won by Vattenfall with a record low bid. Vattenfall was only allowed to place turbines within the boundaries in the figure.

Based on the demand and on the internal grid capacity, the State also decides the capacity of the farm. The capacity of a farm is the maximum production that the specific farm can possibly produce. In practice this means that, in ideal wind conditions, the farm will not produce more than its given capacity. However, as the wind is often not ideal and there are interference (wake) effects between turbines, the observed production of a site is often very different from the capacity of a site. As a matter of fact, average production is about 50% of the installed capacity. This is exactly where our layout optimization plays a role: if we could increase this utilization, we could make a better business case within the auction's rules. We will see in more details later that a higher production can be achieved by locating turbines to reduce their mutual interference by using our optimizers.

The States that organizes the auction also provides valuable information about the site to all companies entering the auction, such as wind statistics in the site, seabed conditions, possible obstacles or natural reserves in the area, position of nearby wind farms, and so on.

The main steps in the design of a new offshore wind farm

With all this information at hand, the first task the design engineers normally face is to decide where to locate the turbines - we refer to this task as the *Wind Farm Layout Optimization Problem* (Figure 1., central plot).

Once the turbine positions are decided, the layout is generally forwarded to the electrical team. Offshore turbines need to be connected to shore with cables. All the turbines are connected with cables to offshore substation(s) where all the energy is collected before being transmitted to the main grid. Connections between turbines and from turbines to a substation are called *Inter-Array Cable Connections*. Another high-voltage cable (called *export cable*) transmits the energy from the substation(s) to shore. Depending on the specific auction, the substation and its connection to shore can eventually be provided by the Transmission System Operator (TSO) of the country or can be part of the scope for the wind farm developer. The optimizer as presented in this paper relates to the first case where the substation position and its limitations are already defined at auction phase and is supposed to be built and operated by the TSO. In case of multiple substations each turbine can route its energy to any substation, but the substation has a maximum capacity, that is often expressed as a maximum number of cables that can be connected to each substation. Different types of cables, with different capacities, electrical resistances and purchase prices, can be used by Vattenfall to connect its turbines to the substation(s). The inter-array *Cable Routing Optimization Problem* is the problem of deciding how to connect turbines and what kind of cable to use in the connection, to minimize immediate and long-term costs (Figure 1., right plot).

Figure 1. This figure illustrates the main steps (from left to right) in the design of a wind farm at Danish Kriegers Flak.

Note: The area available (left-most plot) is given in the auction, then the turbine locations are chosen (central plot), and finally the inter-array cable connection is designed (right-most plot). Dots within the boundaries represent turbines. In this case, the optimization needs to consider an already existing farm (light dots in the lower right of each plot).

The finalized layout and cable routing go through a complete business case validation, which includes turbine foundation design, operations and maintenance assessment, risk analysis, negotiations with manufacturers, etc.

Finally, the wind farm developers tender their bids, and the company willing to provide energy requiring the lowest subsidy will win the rights to construct and operate the new farm, getting the revenues from selling the resulting energy production. Vattenfall decided to invest in developing new optimization methods in the design phase (on wind farm layout and cable routing in particular) as it identified layout and cable routings as important and differentiating factors with respect to the competitors.

Wind farm layout optimization

In this section, we describe the *Wind Farm Layout Optimization Problem*, and provide more details on the characteristic of the problem, on its challenges and on our solution methods. We use some real-world examples to illustrate the design process.

As we already discussed, an area is typically given at the tender phase. As an example, the leftmost plot of Figure 1shows the area available for a Danish wind farm (Danish Kriegers Flak). In this case, the entire area was divided in two sites (within the two boundaries in the figure). Generally speaking, the entire area is optimized in the same optimization run, but there may be some site-specific limitations, e.g., each site may have its own capacity in terms of maximum production.

The overall area available may go through some pre-processing, which may prevent the use of some positions, for example, if there are natural reserves or obstacles in the area such as ship wrecks. Vattenfall´s turbine experts also pre-select a set of turbine models that could be used. Different turbines have different dimensions, different power productions and different purchase prices. To understand the variability in turbine models consider their evolution: modern turbines are much bigger and can produce considerably more energy at the same wind conditions than old turbines. The turbines used 20 years ago, for example, could produce at most 2MW and were as tall as the Statue of Liberty. The largest turbines being announced to the marked in the moment are in the 10-12MW class (Vestas 2019) (GE 2019) and can produce 10MW and are more than twice as tall. Also, within modern turbines there is high variability, especially in performance (how much it can produce at a certain wind speed) and purchase prices.

The selection of turbine models for a specific site is based on direct negotiations with the suppliers and analyses on the options available. Only one turbine model is used in a farm, due to economy of scale and easier maintenance. For this reason, at each optimization run, a single turbine model is considered. What-if analyses are run afterwards to compare the designs for each turbine model and to select the most valuable, based on the final business case. Other constraints, such as a minimum distance between turbines, are often considered. The optimizer must decide where to exactly place turbines in the area available so that the best profit is achieved (central plot of Figure 1). This means maximizing revenues (i.e., power production) and minimizing position-related costs (while considering all the limitations and the variability of the wind in the specific site).

The main revenue source in a wind farm is the produced energy, so it is key to maximize power production. When maximizing power production, the optimization needs to consider the interference phenomenon (wake effect): which is when the upwind turbine creates a shadow on the downstream turbine (see Figure 2).

This is important in the design of the layout since the wake effect results in a substantial loss of power production for the downstream turbines, which are also subject to a possibly strong turbulence. (Barthelmie et al. 2009) estimated that, in large offshore wind farms, the average power loss due to turbine wakes is around 10–20% of the total energy production. It is then obvious that power production can significantly increase if the farm layout is designed to reduce this interference. Wake effect can be caused also by nearby farms, that therefore needs to be considered in the optimization.

Figure 2. This image from a real-world site illustrates the Wake Effect.

Note: the turbines in the interference cone will have a reduced production, highly impacting the overall productivity of the site [Vattenfall]

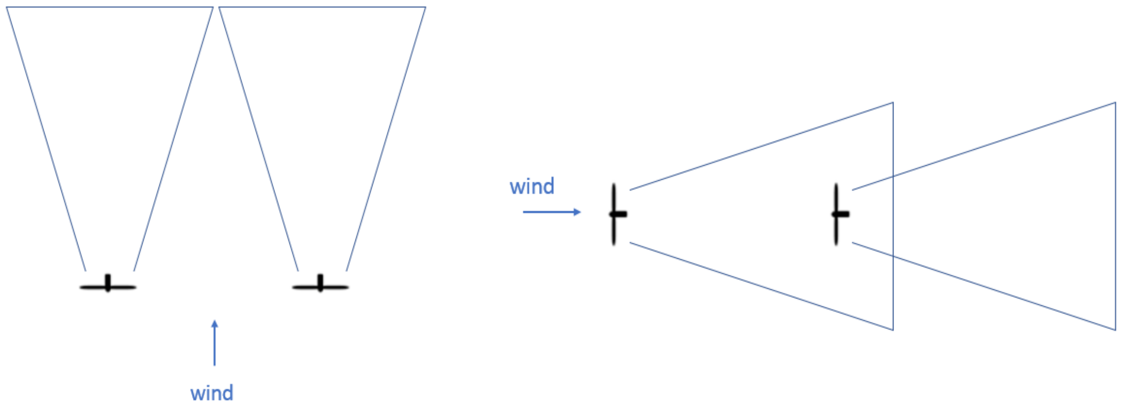
Once we construct a turbine, it cannot be moved: its position is fixed. Nevertheless, the wind highly varies in the site, both in intensity and direction; therefore, that same position can be very good or very bad in relation with the other turbines, depending on the wind. Figure 3 shows a simple graphical example to illustrate the situation. The same configuration can be ideal for a certain wind (first plot) or highly suboptimal if the wind direction changes (second plot).

The wind farm layout optimization problem is challenging. First of all, interference between turbines is a complex natural phenomenon that only can be modelled using non-linear equations.

Second, it is a large-scale problem: in practical cases we are given sites with more than 20,000 possible positions to consider. So, the key question is at which of those 20,000 positions (binary decision variables) a turbine should be installed.

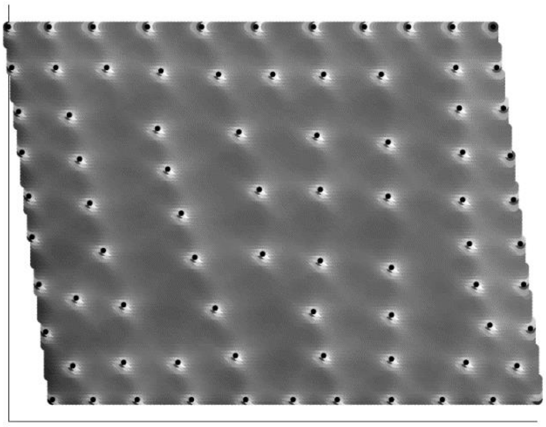
In (Fischetti and Monaci 2016), our approach was to first develop an original mathematical model, where the objective is to maximize profit (which includes revenue from energy selling – so we are implicitly maximizing production and minimizing wake effect- and position-related costs). We consider the non-linearities of wake effect by precomputing the interference matrix reporting, for each possible pair of positions in the site, an estimated power lost due to wake effect. A main advantage of our model, compared with the literature, is that it allows us to consider the full wind variability when optimizing the turbine position. . We assume wind variability to be a discrete random variable., i.e., we deal with a finite number of scenarios, each occurring with a given probability. Both the ideal power generated (also called "gross production") and the power lost for the wake effect are then computed as a weighted combination of the same figures in each scenario, where the weight of each scenario corresponds to its probability. This pre-computation simplifies the model by linearizing the wake effect and adjusting for wind variability. This allowed us to use MIP methods to describe the problem and to use commercial MIP solvers to optimize it.

Figure 3 The wake effect varies depending on the direction the wind blows. When the wind blows from south, the turbine position is ideal, and the turbines produce their maximum energy. The same turbine position is instead quite bad, if the wind blows from west (for example). Turbines automatically rotate to always face the wind.



The problem becomes extremely complex in real applications where more than 50 turbines need to be located while considering the full variability of wind. To fully capture the wind variability in practical applications, we need to consider hundreds of thousands of wind scenarios (each with a given probability). To give the reader an understanding of the complexity, we plot in Figure 4 the overall interference for an optimization run with real-world wind scenarios (here from the Horns Rev 1 farm, an old wind farm in Denmark with shared ownership between Vattenfall and Ørsted). In this case, we had more than 200,000 wind scenarios, so there are so many overlapping interference cones that they are not recognizable any longer.

Figure 4. Horns Rev 1 optimized layout. The shades in the background represent interference (light areas have higher interference while dark areas have no interference). Black dots represent turbines.



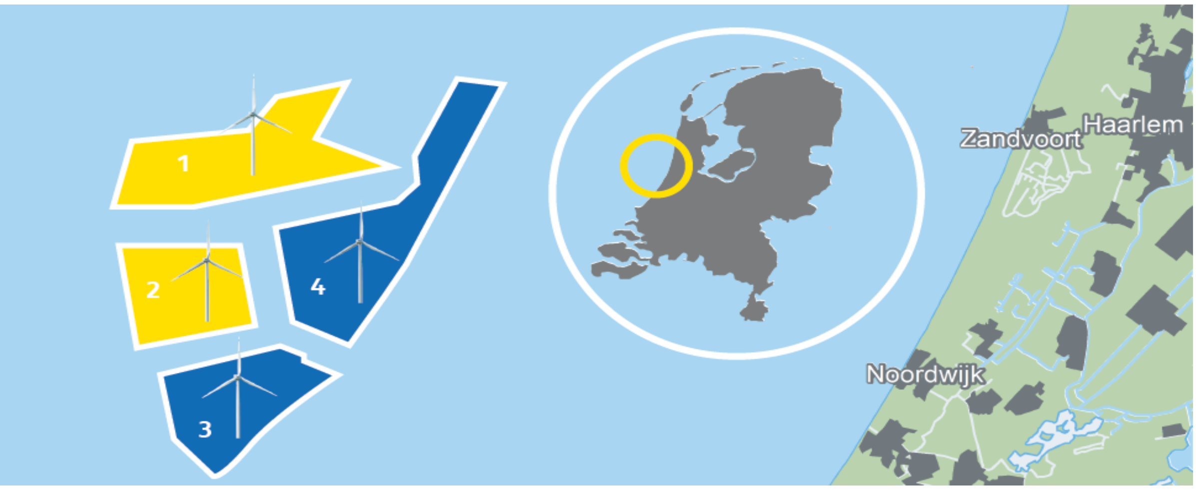
In (Fischetti and Monaci 2016), we designed a MIP formulation for the problem capable of handling stochastic effects (as summarized above using probability weighted averages), even for real cases with hundreds of thousands of possible scenarios; we also developed a fast heuristic algorithm that can handle instances with more than 20,000 potential positions in a matter of minutes. We used both the MIP model and the heuristic in a synergistic way (in a so-called *matheuristic* framework, see Fischetti and Fischetti 2016). In particular, the fast ad-hoc heuristic algorithm is used to produce an initial feasible layout. Possible solutions in the neighborhood of the current solution are then explored using the proximity search paradigm, see (Fischetti and Monaci 2014). According to this framework, we define an auxiliary MIP in which a cutoff constraint is imposed and the objective function is replaced by the distance with respect to the current incumbent, and a MIP solver is used as a black box to produce a new (improving) solution. To strengthen the framework in case of many possible positions, we randomly restrict the number of candidate points at each iteration to a fix number of possible positions (2000). The restricted number of variables at each iteration and the Proximity Search method MIP reformulation prove to be very effective in practice.At each iteration of the matheuristic algorithm, the vast majority of the turbine location assignments are fixed, and the MIP examines the possibility of assigning turbines to only a small subset of the possible locations. Computational results on medium-to-large real instances show that this approach outperforms a standard use of classical local search methods, as well as the use of commercial software packages for wind farm layout design available on the market.

Case study on two wind farms—optimized layouts save over 10 million euros at each

To illustrate the direct impact of using our optimization tools, we will next consider the Hollandse Kust Zuid 1 and 2 wind farm, an auction won by Vattenfall in 2018 using our optimizers. This project is important for the overall offshore wind energy business as it will be the first wind farm in the world to be built without any subsidies.

The Hollandse Kust Zuid area was divided into 4 sites (see Figure 5): Sites 1 and 2 were awarded in a first auction, while Sites 3 and 4 were to be auctioned in a second phase.

Figure 5. Hollandse Kust Zuid 1 and 2 auction was won by Vattenfall in 2018 using our optimizers for wind farm design and cable routing [Vattenfall]



Note: Hollandse Kust Zuid 1 and 2 will be the first sites ever to be constructed without requiring any subsidies

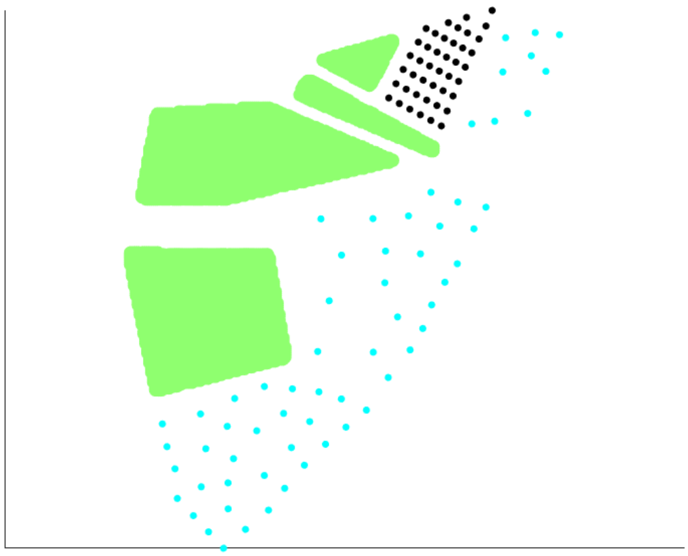
Here we will focus on the first auction, so only sites 1 and 2 (optimized together) are considered. After excluding some positions due to obstacles, the overall area available was defined as shown in solid in Figure 6. As mentioned earlier, it is important to consider the wake effect from nearby farms, so the wind farm layout optimizer received as input also information about a nearby existing farm (dark dots in Figure 6).

This specific auction had an extra challenge: it was known that Sites 3 and 4 would be auctioned in a second stage, hence in the future there will be farms interfering with the farm in Sites 1 and 2. Nevertheless, the positions of these future turbines are, of course, not yet known.

Vattenfall therefore used our tools to also estimate how a future wind farm in Sites 3 and 4 may look like (light dots in Figure 6). The resulting information given for the optimization of Sites 1 and 2 was then:

- the available area (solid in Figure 6)
- the existing farm nearby (dark dots in Figure 6)
- an estimate of future farms nearby (light dots in Figure 6)
- the wind statistics of each site.

Figure 6. The input to our optimization tool includes: available area (four solid areas), existing farms (dark dots) and future farms (light dots)

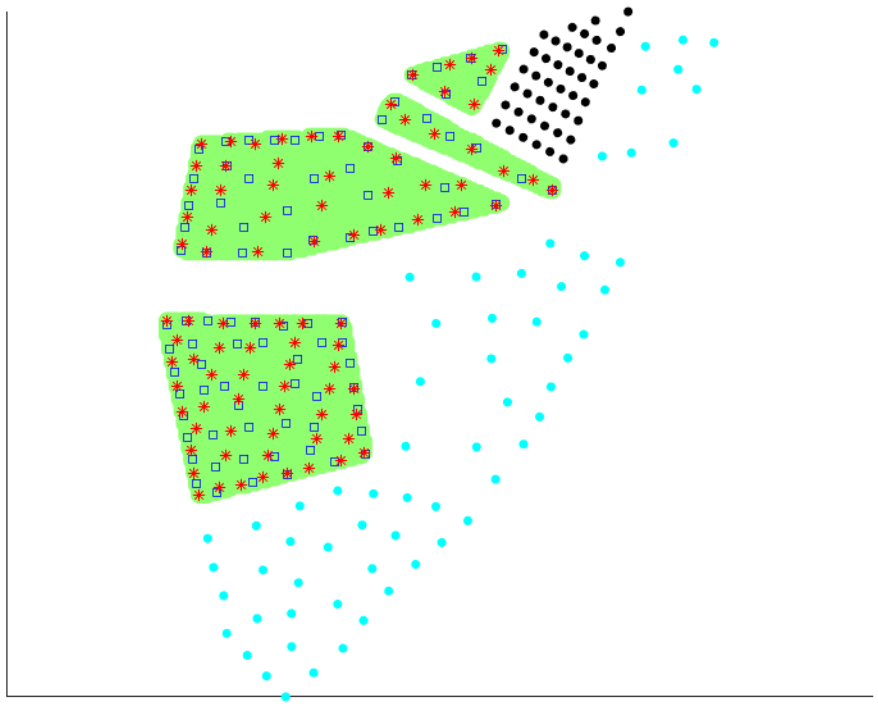


In that specific example, we were asked to optimize the position of 90 turbines, 45 of which should be located in site 1 and 45 in site 2. These numbers were based on the capacity requirements specified in the auction. The objective was to maximize power production, considering also the interference from the surrounding farms. (Position-related costs were not relevant for this example as water and soil conditions are very regular on this site) . The stars in Figure 7 represent the layout suggested by the optimizer (for confidentiality issues the reported layout does not refer to the final layout used by Vattenfall in their tender, but to an initial case where we did a direct comparison with pre-existing in-house tools).

To understand the impact of using the optimization tool, our layout was compared with a layout developed in parallel by the company experts with traditional tools (shown as squares in 7).

To have a fair comparison, both layouts were optimized looking at production maximization, and finally evaluated by a third independent simulation tool.

Figure 7. The optimized layout using our tool (stars) is compared with the one obtained by traditional methods (squares)

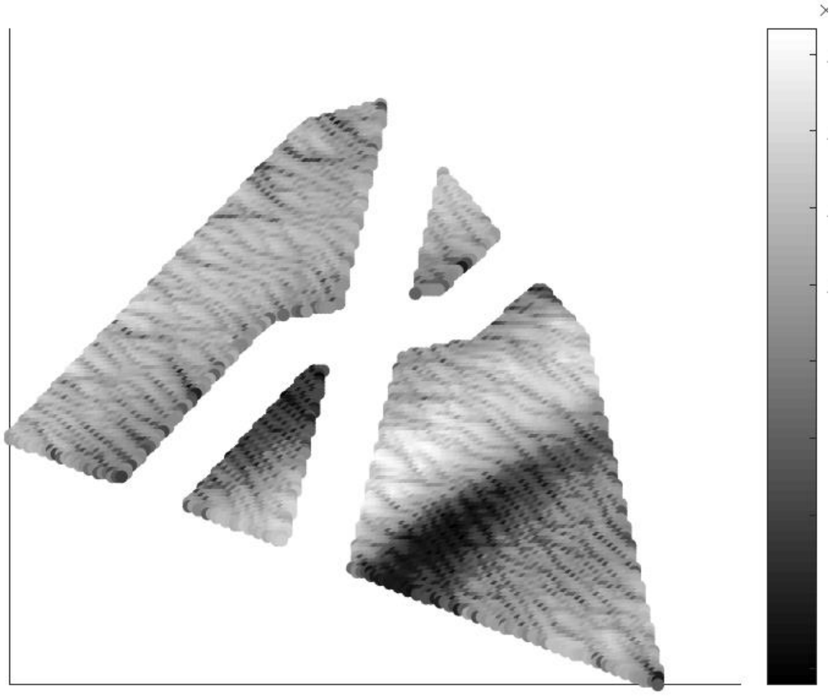


The optimized layout provided higher annual energy production. The difference has been evaluated to be worth 10.2 M€ (Net Present Value) over the farm's lifetime. This extra gain was achieved by a smarter location of turbines in the site. Having a higher production with the same immediate costs implies having a competitive advantage at the auction phase.

Other components may come into play when designing a farm as, for example, the cost of foundations. Hollandse Kust Zuid had a regular seabed, so costs of building the foundation were varying so little that they were not considered relevant for the optimization. Nevertheless, for other wind farms, different depths and the soil conditions impact the foundation costs as different amount of steel will be needed in the design and installation of each turbine.

This translates in associating a position-specific cost to each possible location in the site and it can make an impact on the final layout. The objective of our optimization model—for use on other projects—was thus modified to maximize the revenue from energy production minus the costs related to foundations. As an illustrative example, we can consider a real-world site like Borssele 1, shown in Figure 8, where different foundation costs are represented with different shading. The lightest areas are the most expensive ones; the dark areas have the lowest cost. Actual costs are not reported for confidentiality reasons.

Figure8. The cost for foundations in different parts of a site may be very different. In this plot different shading represents different costs of foundations for a real site (Borssele 1). (Darkest = cheapest, lightes=most expensive), see (Fischetti and Pisinger 2019).



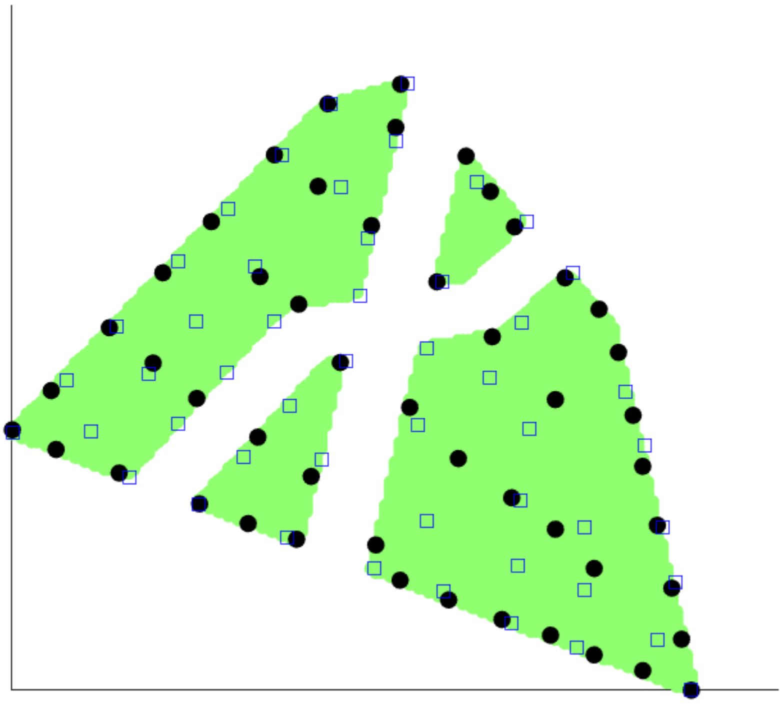
The foundation costs were not considered in the commercial software previously used in the company, so earlier the layout was first optimized based only on power production, and afterwards the turbines in the most expensive positions were manually moved. The result from this process for this specific case is shown in Figure 9(squares).

Our optimization tool explicitly considered these foundation costs as part of the layout optimization. This means that the optimizer makes an optimal trade-off between extra costs of foundation development and extra revenue for higher production, and the proposed optimized layout (dots in Figure 9) considers both costs and wake effect minimization.

Comparing the two layouts, the company experts confirmed that the optimized layout allows for an extra 0.28% in power production (resulting in about 2.6 M€ extra gain) while decreasing the foundation cost (less steel used) (of more than 10 M€). In total, they estimated an increased profit of 12.6 M€ (Net Present Value) over the farm's lifetime using our optimizers on this specific project, compared to the previously used methods.

These estimates of production and costs have been determined by Vattenfall´s experts and are considered to be accurate. Indeed, the entire wind business is based on selling energy and setting the right bid level. Vattenfall has therefore built up a strong expertise in production estimates and in layout evaluation. Without it, it would risk submitting overly aggressive bids and have a negative return of investment, which could have severe impact on the company's financial situation, given the amount of money invested.

Figure 9. We compare our optimized layout (dots) and the one designed with the previous process (squares)

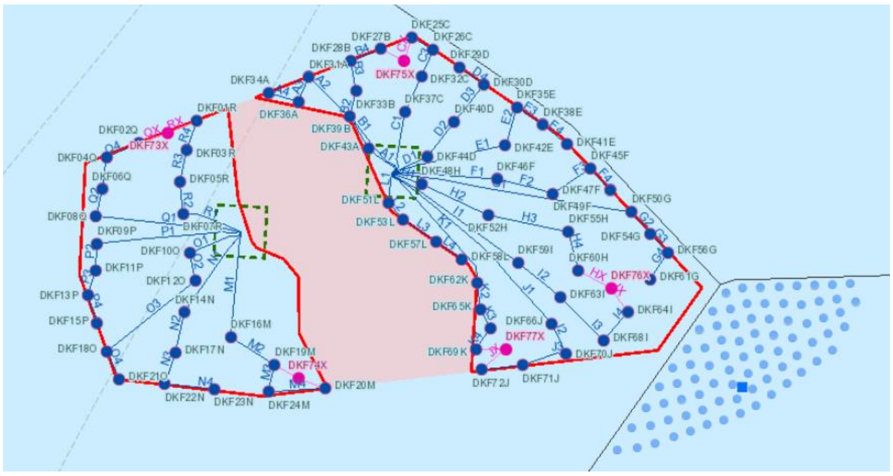


Cable Routing Optimization

The previous examples illustrated the usage of our wind farm layout optimization tool on some real cases, and its impact on each farm. The next step in the wind farm design process is to optimize the inter-array cable routing. This is the task of connecting all the turbines (in the positions preselected by the layout tool) to one or more given offshore substation(s).

Figure 10shows an example for Vattenfall´s farm Danish Kriegers Flak: given the position of the turbines (dots) and the position of the substations (in the dashed squares) our optimization tool was asked to determine the cable connections between turbines in each site and also to the substations (result shown as lines).

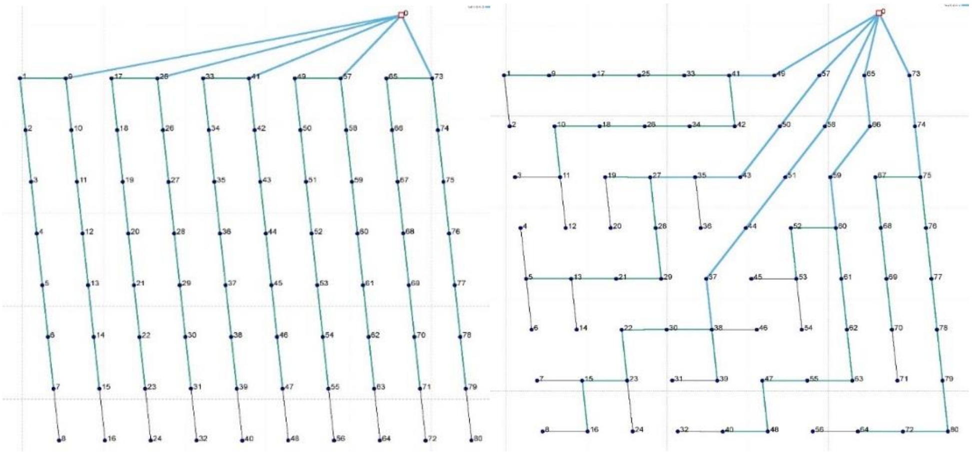
Figure 10. The cable routing was optimized for Danish Kriegers Flak



The optimizer is given a set of possible cables, each characterized by purchase price per meter, capacity, and different electrical characteristics. The optimizer must decide not only how to connect the turbines, but also what kind of cable to use in the connection, minimizing both immediate and long-term costs. The main binary decision variable of our MIP model is whether or not one particular turbine should be connected with another particular turbine (or substation) using a specific cable type. Different constraints arise in practical applications, such as obstacles in the area (that the cables need to avoid), number of cable connection limitations (both for turbines and substations), capacity limitations for each cable type, etc. An additional challenge is the non-crossing constraint: a cable laying over another one has a high risk to damage the cable underneath, resulting in production and revenue losses. For this reason, cable crossings should generally be avoided in practice. In (Fischetti and Pisinger 2017), we developed an original mathematical model that captures the full complexity of the problem, including all the constraints listed above (some of which are challenging from an optimization perspective, as for example the non-crossing constraints). The objective is to minimize costs, considering both the immediate costs (to purchase the cables and to install them) as well as long-term costs (as revenue losses due to power losses along the cables). Some real-world cases showed that this problem is challenging in practice, due to a large number of turbines or to particularly limiting constraints. For these cases, we developed a new framework that applies heuristic methods to initially decompose the problem into smaller subproblems and use the strength of the exact methods to solve each subproblem. To be more specific, we relax the problem by dropping the connectivity requirement. Using this relaxation, we could easily obtain, in a few seconds, a (possibly, disconnected) solution, that is used to derive a feasible solution as follows: we fix some arcs (connections between turbines) of the relaxed solution (according to different heuristics strategies) in the MIP model, and re-optimize on the remaining arcs. The process is repeated until a “good” feasible solution is found. The MIP solver is then warm-started with this solution and run on the full instance, to (hopefully) provide the proven optimal solution. This method proved to be very effective also on complex real-world instances; please see (Fischetti and Pisinger 2017) for more details.

Using our optimizer over the manual solution of the problem allowed for large savings. As an illustration, we again consider the Horns Rev 1 wind farm, in Denmark; the wind patterns of its optimized layout were shown earlier in Figure 4. We had three types of cables we could use in the connections: the cheapest one (85euro/m) can support the current of one turbine only, the intermediate (125euro/m) can support 8 turbines, and the most expensive (240euro/m) 16 turbines. We considered an additional cost of 260euro/m related to installation costs for each turbine type.

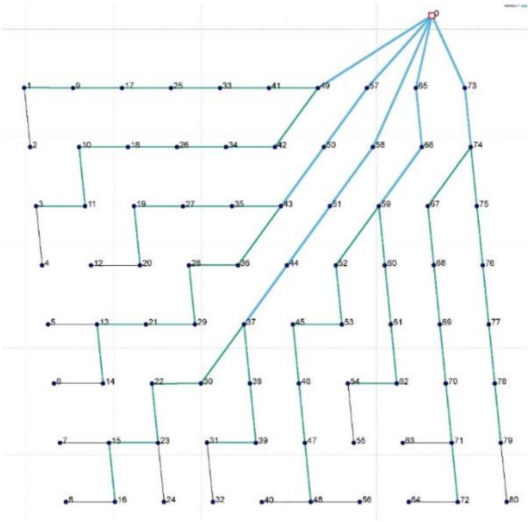
Error! Reference source not found.*. The left plot shows the cable connections for this site that were obtained manually, and the right plot shows the optimal cable connections.*



We fed the same information used by the practitioners into our inter-array cable routing optimizer, with the objective of minimizing the overall cost of the cables, obtaining the layout in **Error! Reference source not found.** (right plot): this layout is very different (less regular) from the manually constructed one, but also more than 1.5 M€ cheaper at construction time. In this example, we focused on minimizing immediate costs only. However, when the energy is transmitted through a cable, there is a power loss due to the electrical resistance of the cable, which translates into a revenue loss, as less energy reaches the collection point. Different types of cable have different electrical resistances, so one cable type may cause higher losses than another. In practice, often the cables with lower resistances are also more expensive, so how to balance between the two costs is an interesting optimization question. To answer this question, we included energy losses explicitly in our optimization, see (Fischetti and Pisinger 2017), allowing Vattenfall to design cable networks that minimize both immediate costs and (long-term) power losses in the cables.

We can also consider other long-term costs in our optimization: applying our tool to the Horns Rev 1 example, we designed a layout that simultaneously optimizes both immediate costs (costs to purchase and install the cables) and long-term costs (revenue losses over the farm's lifetime). The optimized layout according to these criteria is shown in Figure 12.

Figure 12. Our optimized layout, minimizing both immediate costs and revenue losses due to power losses on the cables (Horns Rev 1), see (Fischetti and Pisinger 2019).



This layout is still cheaper at construction time than the manually constructed: during the farm’s lifetime it is estimated to be more than 1.7M€ more profitable.

Project evolution and challenges

In the previous sections we explained the offshore wind farm design problem and the tools we developed to solve it, giving also some practical examples of their usage in Vattenfall. In this section, we discuss the project history and evolution.

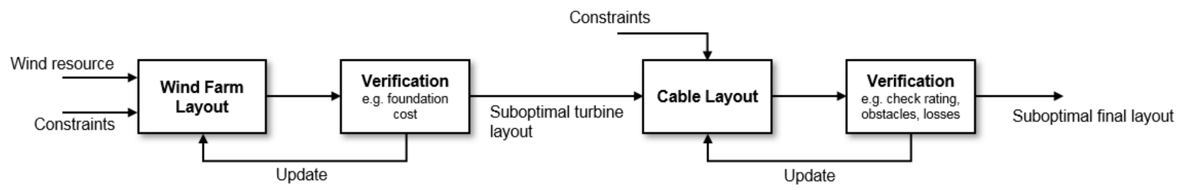
This multiphase project began formally in January 2015 when an industrial PhD project was initiated. (However, earlier work identified the opportunity, which was first investigated as a master project in 2014.) The first validation of our optimization tools on a real auction was carried out in 2016, and in 2017 the system was fully rolled out across the organization. Today, our optimizers are used to define turbine layout and cable routing for all tenders.

Phase 0: Opportunity Identified

In the past, the wind farm design process was completely manual. Farms designed manually can easily be spotted as their layout is very regular (grid-like) and nice looking for human eyes. The design process was based on aesthetic and the “conventional wisdom” that turbines in line are easier to connect. After operating these kinds of farm for some years, it was clear that these solutions were highly suboptimal, and a lot of potential power was lost due to wind wakes.

Vattenfall soon realized that the wind farm layout was a too complex challenge to handle manually, so a search for commercial software to support their layout designing was initiated. Even using the best tools on the market, however, the results looked suboptimal as many constraints arising in practice were not considered. Using these pieces of software, Vattenfall´s wind farm design was a multi-step process still heavily depending on the experience of the engineers. The wind farm layout definition was purely based on power production and the layout was then manually updated to consider other factors, such as foundation costs. The cable routing was ‘drawn with pen on paper’, and then updated according to post verifications (on, for example, power losses). The process (Figure 13) was time-consuming and resulted in suboptimal layouts.

Figure 13. The traditional wind farm design process: a time-consuming step-by step process, with many people involved



As no commercial software met Vattenfall’s needs, our project started.

Phase 1: Proof-of-concept and problems investigation

The first investigation of the problems was carried out by Martina Fischetti for her master thesis project in 2014, in which Vattenfall collaborated with University of Padova and Aalborg University (Fischetti 2014). In particular Aalborg University created the link between the company and the academia during an international master thesis program. The thesis was developed with supervision from Aalborg and Padova Universities and Vattenfall. The wind farm layout and the inter-array cable routing problems were identified as key aspects of the offshore wind farm design process, and we investigated if OR techniques (at that time seldomly used in the wind energy business) could contribute to solving these problems.

During this 9-month phase, the main characteristics of the two problems were studied and modelled using MIP techniques and heuristic algorithms. The newly developed methods were compared in detail with similar models in the literature, and further developed to outperform them.

The preliminary results from the master thesis convinced Vattenfall to further investigate the topic. Vattenfall hired Fischetti and sponsored her PhD on the project at Denmark´s Technical University (DTU)—which has a strong OR program in Denmark.

Phase 2: Close inter-disciplinary collaboration

The Industrial PhD project (Fischetti 2018) strengthened the collaboration between academia and industry. The first part of Phase 2 was dedicated to presenting the ideas and the preliminary results obtained in the master thesis project across the organization, collecting feedbacks from the different experts at Vattenfall. Being a multi-disciplinary project, this phase was key to the success of the project, as mathematical background met electrical expertise, wind modeling knowledge, geographical understanding, and process thinking. The main challenge here was to let all these different actors talk the same language. Primarily, we communicated with the mathematical optimization language, so we had to study various rules of thumb used in the manual processes, to understand if they were hard or soft constraints, and how they should be properly formalized.

OR had not been well known in Vattenfall, so a challenge was also to convince the senior and experienced engineers that we could contribute to their daily work and its improvement, even without being experts in their specific field. In this challenge, we worked step-by-step with them, with many iterations and feedback loops, and the quantified results convinced them to trust the final software.

Facing real-world instances, and more and more considerations arising in practice, pushed us to develop multiple updates of the initial software, and to find innovative solutions to solve the practical problems at hand. An example is the cable routing optimizer: when facing more complex instances, the initially developed model was not effective enough, so we had to design a new solution framework around the mathematical model. Company experts suggested also new technical challenges, for example, to consider power losses in the electrical cables. For many years, there were many un-answered questions in the electrical team: how to balance between long-term costs and the immediate cable costs in an optimal way? Would the cable routing be different if these aspects were considered? Working together and properly modeling these questions in our optimizers, allowed us to finally find a quantitative answer to them.

The collaboration with different teams (Wind and site, Market development, Engineering, Procurement, R&D) enabled us to understand the newest challenges, constantly arising in this quickly evolving business, where both auction rules and available technology can change. Some examples of these challenges for the cable routing problem include considering more failure-robust structures and new technologies on the market as explained in (Fischetti and Pisinger 2018).

Phase 3: Validation in a real auction

In 2016, our optimization tools reached maturity and were fully validated in a real auction for the first time. We were directly involved, joining the wind farm development team. This is a multidisciplinary team associated to the specific farm in auction, which goal is to design the complete farm and find the best business case for the bid. In this phase, we worked closely with the experts in charge of the layout definition. We studied their process and aligned with them on the specific functions they were using to model wind and other factors. Once the objective functions and constraints were aligned, we provided the wind farm project manager with alternative layouts. The experts in the evaluation team used a third software to validate our results, quantifying the savings from using our tools over their traditional methods.

This opened up a vibrant exploring phase, where we supported the wind farm development team with different what-if analyses, as for example the one concerning the evaluation of foundation costs that we discussed in the previous section. This analysis, in particular, opened up the discussion with the foundation team, that developed a new model to estimate the cost map for our optimizer (see Figure 8 for an illustrative example). This illustrates how different groups, with different expertise and using different tools, can interact with our optimizers to improve the overall understanding of the project itself and to attain better business results. After this successful validation, the tool was ready to be used in all Vattenfall´s tenders.

Phase 4: deployment across the organization

After Phase 3, the value of our tools was clear. At this point, the product was ready to be rolled out across the organization. More and more project teams asked us to provide optimized layouts and cable routes, so there was the need to have more people using the optimizers. At the same time, realizing that the optimization routines outperformed what could be found in the industry, Vattenfall looked to the future and began development of a complete model framework around the optimizers for a bigger purpose. The idea of having a more automatic design of farms and a systematic way of collecting information was presented to and accepted by executives at Vattenfall. Our optimizers contributed to a path for digitalization and more data-driven decisions in the overall design evaluation.

This was a great challenge as it involved changing the traditional way of working for many people. Eventually, this process resulted in a big success. This new way of working enabled the creation of a new organizational unit called Windfarm Design, with one of its departments, System Design, having a group of OR specialists and modelling experts making early assessment of new ways of building wind farms and helping in the design for Vattenfall´s offshore wind pipeline.

The impact of the optimization tools thus reaches well outside the specific immediate benefits, and includes supporting tender preparation, maturing projects under preparation and construction, improving existing assets and identifying new promising sea areas to build future windfarms. Overall, this work impacts the entire value chain of Vattenfall offshore wind.

Phase 5: driving technology development

The usage of the optimizers and the modeling framework around them allowed Vattenfall to have a new engagement also with manufacturers. Vattenfall worked in close collaboration with, for example, turbine manufacturers to ensure the most profitable performance for a specific turbine model. As we explained before, the production of a certain model of turbine depends on the wind. The function that translates wind in MW production is turbine-specific and can be tweaked by the manufacturer (changing some components of the turbine or applying different control strategies). Vattenfall used our optimizers to run what-if analyses on these variants to assess their value. In this way, the manufacturer could supply a cost-benefit optimized site-specific turbine, designed to the specific conditions of the farm of interest. This has been evaluated to have a huge impact on the overall farm production, allowing significant more production for each farm with the same initial investment. This development together with the manufacturer would have been impossible without an analytics mind set, a flexible optimization routine and a streamlined business process.

Phase 6: The future

The wind business is a fast-evolving field; thus, our optimizers need to always be up to date, with the newest technologies coming on the market, as well as with the new auction rules across the different countries. Furthermore, the tools need to be updated to allow innovative thinking: as already mentioned, the tools are currently used to open discussion with suppliers and drive the future development of the technology. Therefore, even if Phase 4 concludes the deployment of the software as described here, new phases are expected in the future, to further enrich the optimizers and to develop new mathematical models to support them, in this quickly changing world.

A new challenge that Vattenfall is investigating, is the integration of the actual wind farm design (turbine layout) and cable routing tools in a unique tool. This is a difficult mathematical problem as it merges two large-size complex problems. Given the fact that the dominating monetary impact is in the increased revenue from the first tool (wind farm layout), we are currently investigating if and how much an integrated tool would provide of value.

Vattenfall plans to continue to collaborate with leading universities to further investigate this and other optimization topics in the wind business. More specifically,

as still more wind farms are being established, we plan to look into developing solutions for efficient maintenance and repair. Other interesting topics are in logistics and construction planning for offshore wind farms.

Additional Impacts of using our optimizers

The optimizers have several advantages for the company, as they enable large direct gains for each wind farm, giving a competitive advantage at auctions. In addition, they provide a more analytical and data-driven approach to the design (re-thinking conventional wisdom and rules of thumb) of wind farms, a more streamlined and transparent process, and enabling more innovative thinking.

Huge savings and increased competitiveness at auctions

Considering both the extra gains and the savings from the wind farm layout and cable routing, the estimated direct impact of using our optimizers instead of traditional methods is of magnitude 10-15 M€ for a standard 350MW farm, and thus of more than 150 M€ overall - just looking at sites that Vattenfall already has right to build and where our tools have been used as of today (which sum up to about 6GW). In Vattenfall´s strategy for the wind business area, it has been announced that by 2025 Vattenfall will more than double its operational renewables portfolio compared to 2020, thus the gains from the usage of our tools will significantly grow.

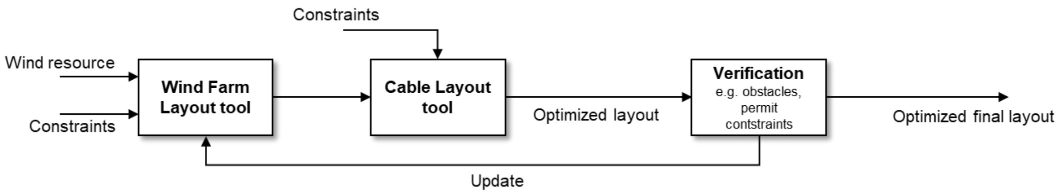
The optimizers have, as mentioned before, already been used on a number of 'soon to be built' real world farms, for example Kriegers Flak in Denmark and Hollandse Kust Zuid (Sites 1 and 2) in The Netherland, both won with record low bids. In particular, Hollandse Kust Zuid (Sites 1 and 2) was won with no subsidies—the first time in the world an offshore wind warm is to be built without any subsidies. The implications for the long-term use of wind power—as an economic competitor of fossil fuels—are momentous for sustaining our planet.

Through the development and use of the optimizers, Vattenfall has secured an increased competitiveness in bids and this is of key values for its business. These gains are based on direct layout comparison with traditional methods (as we have seen in the examples in the previous sections) but there are also more savings that have been initiated by the use of our optimizers.

A faster and more effective process

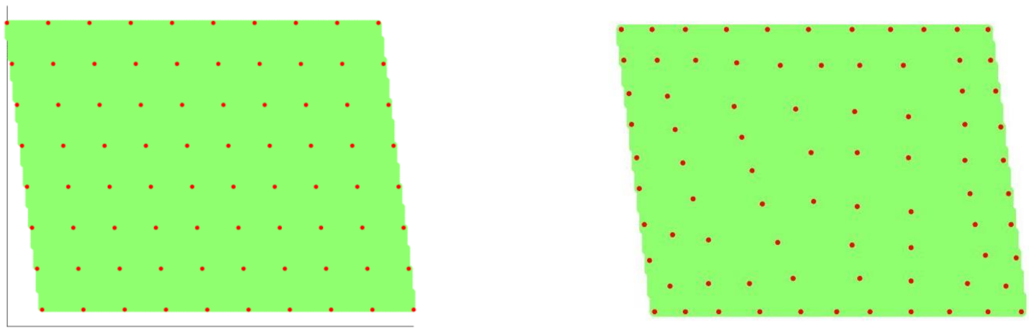
Comparing with the commercial software available on the market (mainly developed by engineers with a wind background and not OR experts) we used different and more advanced optimization methods. Compared with the previously existing process, our tools enabled us to standardize the procedure across different farms under development. They also enabled us to sensibly shorten the time needed to get to a full business case (from weeks to hours). Compared with the previous process (Figure 13) the new process was streamlined, and all factors were considered explicitly in the optimisers (Figure 14), without the need of time-consuming cycles in the process.

Figure 14. The new streamlined process includes all factors explicitly in the optimization.



In contrast with the conventional approach of locating turbines in a regular layout, our results showed that optimized layouts tend to maximize the usage of the borders of the area and are not necessarily regular. Figure 15 (right plot) shows how we would have designed Horns Rev 1 if we had our optimizer back then. It can be seen that the optimized layout substantially differs from the existing one.

Figure 15. Horns Rev 1 as it looks today, designed manually (left plot), would have looked differently had our optimizers been used (right plot).



Easily assess alternatives for a better business case

Our tools gave Vattenfall´s experts more time to experiment and quickly assess various alternatives. The experts in the field are still of key importance for the wind farm design process and, in particular, it is their responsibility to feed the optimizers with relevant data. For example, deciding which exact model of a turbine to use is a key point, as this depends on direct negotiation with the supplier, risk analyses and many other factors. The pre-existing multi-step layout design process was taking weeks for a single layout: as indicated in Figure 13, many manual iterations were required and the turbine layout or the cable route would change multiple times in the process (to adapt to the different constraints checked by different groups). In this setting, of course, the time to experiment with (for example) different turbine types was limited. A practitioner would probably decide on a single turbine model and stick with this decision. Getting to a comparable (better) result, takes today only a few hours. Now, thanks to the comprehensive and fast tools, the experts can define a set of interesting turbine models and create a layout and a full business case for all of them. Here we mention the turbine model as an easy example of a wind farm component but, in practice, there are many other components to select, so having a responsive tool is valuable. Many choices and factors considered in the design phase influence each other. When the process was manual it was impossible to properly quantify the impact of each decision on the final business case. Our optimizers enable Vattenfall to make more informed decisions at the design phase. The final decisions are now based on their impact on the final layout and on their production and costs, rather than on rules of thumb.

The optimizers also offered Vattenfall flexibility and capability to test the newest options on the market. This is important in such a fast-developing sector as the farms we are designing today will be constructed perhaps 5-10 years into the future, where bigger and more efficient turbines will be available, together with new types of foundations and cables.

Driving technology development for even greater savings

Vattenfall´s experts can now compare different existing components on the market, and they also constructively approach the manufacturers and drive the development of new components.

A practical example of this is the engagement with wind turbine manufacturers for assessing the potential for using more site-specific turbines that we have discussed in the previous section. This allows Vattenfall to test the newest components on the market and understand if something that looks very promising on paper, actually brings value in the specific site they are tendering. It also allows the evaluation of the synergies in the usage of different components together, as well as quantitatively comparing the effect of using different versions of the same component. This ultimately allows Vattenfall to drive technology development in the most promising direction.

Conclusions

Vattenfall has introduced operational research methods to identify the optimal location of wind turbines in a given site in order to maximise performance and ultimately profits, while reducing costs. By focusing on two complex components of offshore wind farm design, namely wind turbine location and routing for offshore electrical cables, Vattenfall can maximise its power output, expand its pipeline, and is on track to reach its target of enabling fossil free living within one generation.

Until a few years ago OR had never been used in the wind farm design process. However, the results obtained are extremely successful: savings in the order of 10-15 M€ have been achieved when designing each individual wind farm.

The developed OR models and algorithms are now fully integrated within Vattenfall´s wind farm design process, allowing not only for large gains, but also for a more agile overall design process. The optimiser has been used on several real-world farms, among others Kriegers Flak in Denmark and Hollandse Kust Zuid in the Netherlands (that will be the first farm to be constructed subsidy-free).

The use of the OR tools for what-if analyses lead to the establishment of a new “scenario” team, where different layout options for future farms are quickly evaluated and more informed decisions are made. The optimiser also gave momentum to Vattenfall´s experts, allowing them to think out of the box, testing entirely new ideas and solutions by running the optimiser with various design factors as input. The availability of such comprehensive optimisation tools helps Vattenfall to test new ideas and alternative options quickly, and to quantify the impact of new design choices from the very first stages - which would not be possible in the more manual process.

In addition, Vattenfall can now identify which new components make most value for the company, and feed that information to the suppliers, which indirectly has a significantly high value. Thanks to this newly gained capability, Vattenfall can now engage with suppliers in a novel way and drive innovation in a structured and value-oriented way, supporting the overall offshore wind business.

Overall, the project illustrates the impact of using OR in practical wind energy problems. The tools allowed Vattenfall to be more competitive at tender phase, and, more generally, to reduce the required subsidies and to lower offshore wind energy prices. These are key factors for enabling a more sustainable future for the generations to come.

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