Layout Optimisation of Floating Offshore Wind Farms

Minimisation of inter-array cable length while allowing for anchor-sharing in a floating offshore wind farm

C.J.A. (Steyn) Janus

TU Delft

VATTENFALL

Layout Optimisation of Floating Offshore Wind Farms

Minimisation of inter-array cable length while allowing for anchor-sharing in a floating offshore wind farm

by

C.J.A. (Steyn) Janus

to obtain the degree of Master of Science
at the Delft University of Technology
to be defended publicly on January 30, 2024 at 13:00h

Student Number:	4566351	
Project Duration:	March 2023 - January 2024	
Thesis committee:	Dr. A. Bombelli	Supervisor
	Ir. P.C. Roling	Chair
	Dr. A.C. Viré	Examiner
Company Supervisor:	Dr. M.P. Kidd	Vattenfall

Faculty of Aerospace Engineering · Delft University of Technology

Acknowledgements

Embarking on the journey of writing a thesis is much like setting off on a hike. At first, we look up at the challenge before us with excitement and confidence, ready to explore the many different specializations and academic research areas. But just like any hike, the journey of writing a thesis has its ups and downs. Some days pass quickly, while others feel slow and challenging. However, with perseverance and a willingness to make considered choices, we can overcome any obstacles along the way. It's important to remember that the view from the top is always worth the effort we put into it. And with the support of our friends, family, supervisors, and colleagues, we can stay inspired and motivated throughout the entire journey. So keep climbing, keep exploring, and remember that the reward at the end is worth every step of the way.

I would like to express my heartfelt gratitude to my supervisors, Dr. A. Bombelli from TU Delft and Dr. M.P. Kidd from Vattenfall. Their unwavering support and inspiration to explore the unknown, as well as practical brainstorming sessions, have been pivotal in improving the quality of my work. I would also like to thank my colleagues at Vattenfall for their guidance, brainstorming sessions, encouragement, and most importantly, the delightful distractions they provided, which were greatly appreciated.

Further, my sincere appreciation is extended to both the institutions of Vattenfall and TU Delft, whose resources and environments have been indispensable in facilitating my research.

I am immensely grateful for the unwavering support of my family and friends. Their constant encouragement and willingness to listen to my discussions about wind farms and operation research have played a vital role in my journey. I attribute my current achievements and who I am today largely to their unwavering backing. Their support has been a profound source of inspiration for me, and for that, I am deeply thankful.

C.J.A. (Steyn) Janus
Amsterdam, January 2024

Contents

[1] Only of Part I: Scientific Article, for the List of Figures of Part II, see part II.

[2] Only of Part I: Scientific Article, for the List of Tables of Part II, see part II.

Nomenclature

BFOW Bottom-Fixed Offshore Wind

BFOWF Bottom-Fixed Offshore Wind Farm

CAPEX Capital Expenditure

EID Edge Impact Destroy

FOWF Floating Offshore Wind Farm

FOWT Floating Offshore Wind Turbine

GA Genetic Algorithm

HPC High-Performance Computing

LCOE Levelised Cost of Energy

LSILO Local-Search Inspired Layout Optimisation

MILP Mixed-Integer Linear Programming

NPV Net Present Value

O&M Operation and Maintenance

OPEX Operation Expenditure

OR Operations Research

VNS Variable Neighbourhood Search

WFCR Wind Farm Cable Routing

WFLO Wind Farm Layout Optimisation

WFO Wind Farm Optimisation

List of Sets

A Union of A_d over all $d \in D$.

A_d Set of anchor grid points in design $d \in D$.

B Set of designs selected in previous alternatives.

$C_{d_i d_j}$ or C Set of pairs of designs (d_i, d_j) that are conflicting, i.e., cannot coexist.

D Union of D_t over all $t \in T$.

d_a Set of anchors A for each design d.

D_t Set of potential designs for turbine grid point $t \in T$.

FA_a Set of fixed anchors $a \in A$ that will remain at the same anchor grid point.

FTP_t Set of turbine points $t \in T$ that have been selected and will thus not move.

G_d Diversity score of design $d \in D$.

I Set of turbines in the layout.

ND Set of designs that have not been destroyed.

Q Union of all sets $C_{d_i d_j}$, each of which contains a pair of designs that are conflicting.

T Union of T_i over all $i \in I$.

T_i Set of grid points on which turbine i can be placed.

W_d Weight of design $d \in D$.

List of Variables

n number of turbines in a turbine group.

x_t binary decision variable showing selection of turbine grid point t.

y_d binary decision variable showing selection of design d.

z_a binary decision variable showing selection of anchor grid point a.

List of Figures[1]

[1] Only of Part I: Scientific Article, for the List of Figures of Part II, see part II.

List of Tables[2]

[2]Only of Part I: Scientific Article, for the List of Tables of Part II, see part II.

Introduction

During my master's program at TU Delft, I had the opportunity to explore my passions and gain valuable experiences. I had the chance to work with a team, discover the world of operations research, and learn programming in Python. Among the courses that I took, the ones that really caught my interest were airline planning and optimisation, introduction to operations optimisation, and agent-based modelling. With the skills that I have learned, I was eager to apply them to the world of sustainable energy and contribute to the energy transition.

I heard about interesting research being done at Vattenfall, and I started reading about it. I got in touch with the System Design department through a fellow student at TU Delft, and we were both excited to start a thesis project together. The project was particularly interesting because the industry is turning more and more towards floating wind, and it allowed me to integrate the knowledge I have gained during my MSc in Aerospace Engineering.

During the project, I had the privilege of engaging in thought-provoking conversations with industry experts and academics that significantly enhanced the quality of my work. I am thankful for the opportunity to make a contribution to a field that I'm enthusiastic about, with the valuable assistance and direction I have received throughout the process.

The format of this thesis report is structured in two parts. The first part, part I, consists of a scientific paper that covers the essential literature as a background for this research, the formulation of the problem, the methods used to solve it, and the results achieved. The second part of this project, Part II, includes a literature review that expands on the initial research conducted and relevant academic fields.

Part I

Scientific Article

Layout Optimisation of Floating Offshore Wind Farms

Steyn Janus*

Delft

Abstract

This study presents an innovative algorithm designed to optimise the layout of floating offshore wind farms (FOWFs), addressing inter-array cable length and the number of anchor structures required. This research is particularly noteworthy as no prior work has been conducted on wind farm layout optimisation for FOWFs. The Local-Search-Inspired Layout Optimisation (LSILO) algorithm was developed, incorporating a variety of novel heuristics such as Edge Impact Destroy (EID), diversifying repair, and neighbourhood tabu search, most of which were innovatively designed for this research. The LSILO algorithm is capable of optimising cable routing while facilitating anchor-sharing and minimising cable length. In comparison to the industry standard, LSILO displayed promising results, outperforming the random benchmark by a 24% improvement in cable length. However, the algorithm does plateau at a certain turbine density. Turbine density has a substantial influence on the algorithm's speed and rationality. Therefore, we recommend utilising LSILO with an EID of three turbines, diverse repair without alternatives, and traditional tabu search, on current floating wind turbine sites.

1 Introduction

The search for clean and inexhaustible energy sources has intensified as the world pivots from fossil fuels toward a more sustainable energy system. Wind power is a dependable option for renewable energy, especially in offshore locations where the wind is stronger and more consistent [3]. Due to increased impact of visual and noise pollution [20], onshore wind farms typically position themselves in rural areas with a sparse population [11]. Nevertheless, traditional Bottom-Fixed Offshore Wind Farms (BFOWFs) are only economically viable at depths of around 30 meters due to foundational costs [2][5]. This maximum depth constraint of BFOW limits the development of new BFOWFs twofold.

First, many regions around the world, including the west coast of the United States, Japan, and Southern Europe face deeper coastal waters, rendering BFOW a costly solution to their energy needs. Second, shallow waters are increasingly facing diminishing returns due to the saturation of shallow areas and mutual interference between farms [27]. These limitations have sparked a quest to reach deeper waters for wind energy exploitation economically, leading to the realisation of the first Floating Offshore Wind Farms (FOWFs) and increasing the interest in offshore wind for many countries [34]. These farms leverage their crucial characteristic, a floating foundation, to reach deeper waters. Although a few instances have implemented this technology, it requires more clarity regarding cost-effectiveness compared to traditional methods [31].

Optimisation heuristics can help improve cost efficiency by targeting expensive aspects such as cable length [36]. These heuristics have been extensively developed for bottom-fixed wind farms, focusing on minimising cable length and wake loss. They have played a crucial role in making Bottom-Fixed Offshore Wind (BFOW) a significant contributer to the sustainable energy supply [3]. However comparable research on FOWFs has not been published to date, presenting an appealing opportunity for further advacements in the development of FOWFs.

For FOWFs, the increased cost of the wind farm originates mainly from two unique aspects of the floating characteristic. From a top-down perspective, the electrical cables face obstacles created by the uncrossable mooring lines of the anchors, resulting in lengthy cable routing. Where bottom-fixed usually deals with a handful of obstacles, typically boulders, FOWFs have to deal with hundreds, drastically increasing the cable length. The second cost-increasing aspect of FOWFs is the foundation cost, or, in this case, anchor cost. Placing anchors in deep waters causes each anchor's cost to rise rapidly. Luckily, anchors can be shared between turbines [10], which becomes more cost-effective at depths exceeding 400 meters [9].

Therefore, this research aims to develop an algorithm capable of minimising the cable length and reducing the number of anchor structures in an FOWF, focusing on comprehensiveness, practicality, and time efficiency. In this development, the study aims to uncover potential challenges and establish a foundational exploration

*C.J.A. Janus, MSc Student, Sustainable Air Transport, Faculty of Aerospace Engineering, Delft University of Technology

in this domain, as no research has been conducted yet. Additionally, the research will analyse the impact of various site parameters to assess the scalability and robustness of the algorithm. Ultimately, this investigation intends to determine the feasibility of layout optimisation as a significant area of future research for FOWFs.

This thesis is structured as follows. The second section, section 2, discusses the theory of FOWFs. With this, the current state of the literature is reviewed. After this section, the methodology behind the developed algorithm and the reasoning behind it are discussed in section 3. Next, the experiments on the performance of the algorithm and the results of these experiments will be presented and analysed in section 4. Furthermore, the discussion section, section 5, highlights limitations and other considerations following the results and adds a broader context to the results. Finally, the conclusion and future works section, section 6, summarises the main findings and suggests future work in this underdeveloped research area.

2 Literature

No research is published on the layout optimisation of FOWFs. This section therefore provides base knowledge on FOWFs in section 2.1 and section 2.2 reviews the existing literature on BFOWF layout optimisation to investigate overlapping areas.

2.1 Floating Offshore Wind Farms

In this research, an individual Floating Offshore Wind Turbine(FOWT) consists roughly of four components. First, a wind turbine generator captures and converts wind energy into electrical energy. Second, the floating structure supporting the wind turbine utilises the buoyancy of the water as a structural force. Third, a set number of anchors are combined with the mooring lines to stop the turbine from drifting and act as a restraining force. Fourth, the mooring lines themselves, which connect the floating platform to the anchors, ensuring stability and position maintenance.

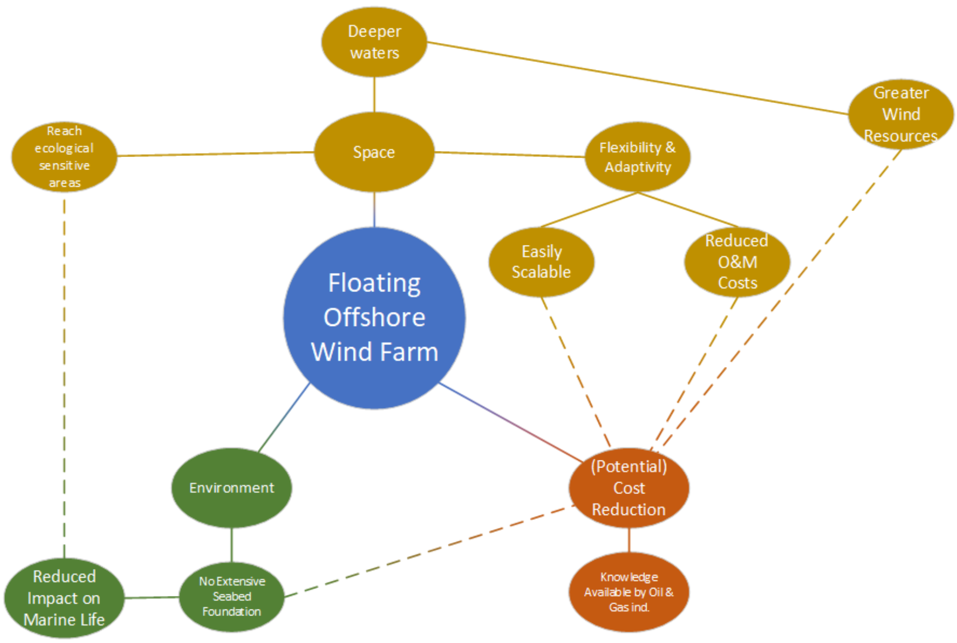


Figure 1: Overview of the benefits of FOWFs over BFOWFs, where dashed lines display synergies.

The differences between an FOWF and an BFOWF are mainly present in two features of the wind farm. First, the foundation of an FOWF consists of a floater, anchors and mooring lines instead of a fixed mono-pile foundation. As stated in section 1, the foundation is the highest avoidable cost due to placing anchors at great depths [21]. A second difference is the inter-array cable connection at the base of the floater. This cable connection requires a floating part to reduce the forces on the cable, such as the lazy wave, steep wave and lazy S [32]. The currently operating FOWFs Hywind [39] and Fukushima [37] employ the lazy wave. A result of these differences is the different wake propagation of an FOWT since the floaters influence the yaw and rotation of the turbine [33].

The distinctive features of employing FOWTs over their bottom-fixed equal lead to advantages in roughly three dimensions: First, space exploitation occurs more effectively. Namely, using FOWTs enables the exploitation of deeper waters, reaching more wind-rich areas. The viable area for wind energy is estimated to increase by a factor of five [26] by implementing FOWFs. Also, FOWTs show more flexible and adaptive use of space. Specifically, the non-permanent nature of an FOWT's foundations enables the FOWTs to relocate in response to changing environmental or operational conditions. An additional benefit in this dimension is that the entire FOWT can be manoeuvre to shore in case of repair operations. This benefit relates to the second dimension in which advantages are prospected: FOWFs are expected to be more environmentally friendly. Firstly, because no large foundations need to be driven into the seabed, reducing the impact on marine life during instalment. However, it is unclear if deeper waters are more or less ecologically sensitive [13]. The final dimension is the potential cost reduction FOWFs anticipate, linking many of the previously stated features, but also the knowledge on floaters of the oil & and gas industry. A graphical overview of these benefits is offered in figure 1.

2.2 Literature Review

As stated in the section introduction, no literature exist on the layout optimisation of FOWFs when this research commenced. In literature, it is found that floating wind turbines present a solution to exploit deep-water wind resources, though their technology is developing and still needs to become cost-competitive [4]. The absence of literature on layout optimisation of FOWFs highlights the complexity of designing layouts for FOWFs. Conventional methods for bottom-fixed wind farms do no suffice and BFOWF optimisation strategies need to be altered towards floating characteristics.

When looking at the current techniques employed in Wind Farm Layout Optimisation (WFLO), it is found that literature currently employs a discrete approach [22], notably using genetic algorithms [25]. These heuristics are praised for their efficiency and quality of solution. While effective for fixed turbines, the strategies do not translate to floating systems due to differing wake behaviours [33]. For Wind Farm Cable Routing (WFCR), a mix of genetic algorithms [17] and Variable Neighbourhood Search (VNS) [8] shows potential. VNS provides an advantageous flexibility for larger, more complex scenarios [38]. The current literature's scarcity of FOWF optimisation points to a distinct research gap, particularly in anchor minimisation and cable length reduction. It recommends a Variable Neighbourhood Search coupled with visibility graphs for WFCR and suggests exploring Mixed-Integer Linear Programming (MILP) and graph theory for anchor optimisation. However, no problems similar to anchor sharing and WFCR for FOWFs are found in the literature.

Finally, the literature identifies Net Present Value (NPV) as a critical success metric, advocating for specialised research in FOWF optimisation techniques to pave the way for more economically and technically viable renewable energy solutions [12]. However, NPV is only sometimes the best measure; if a more separate analysis is necessary, it can be disadvantageous to use one single metric as it can result in a clouded analysis.

2.2.1 Literature Gap

Since no research has been published on the layout optimisation of FOWFs, an extensive research gap has been identified. A clearly defined part of the research gap is vital for manageable research. Given the absence of research on WFCR and anchor sharing for FOWFs, this research strategically delves into minimising the inter-array cable routing and the anchor count by sharing anchors. This is especially intriguing as FOWFs have the potential for substantial cost reduction and cannot use classical WFLO techniques. The critical roles of these specific aspects in achieving more cost-efficient FOWFs, combined with their dissimilarity to other wind farm optimisation heuristics, make them the focus of this study. Developing novel techniques is necessary to address these challenges, further highlighting the relevance of this research.

3 Methods

This section explains the methodology of the research. First, this will be done by offering a graphical overview of the complete algorithm, which can be found in figure 2. After this, the algorithm's scoring method will be explained in section 3.3. Following, the methodology behind creating the sites and the context in which the FOWF will be placed will be explained in section 3.4. Afterwards, the design creation will be explained in section 3.5. This section considers viable design options for every turbine and conflicting inter-turbine designs. Subsequently, the cable routing part of the algorithm will be explained in section 3.6, where the goal is to route the electrical cables as efficiently as possible without crossing mooring lines or other electrical cables. When this is explained, the focus will shift towards anchor sharing, and a methodology to achieve the minimum amount of anchors in a site will be presented in section 3.7.

With the foundation established, the Local-Search-Inspired Layout Optimisation algorithm (LSILO) will be introduced in section 3.8. The LSILO algorithm contains an initial solution phase, a destroy phase, a repair phase, and three different tabu list methodologies. Finally, concluding the LSILO algorithm, anchors will be shared as a by-product, and the methodology behind this heuristic will also be explained.

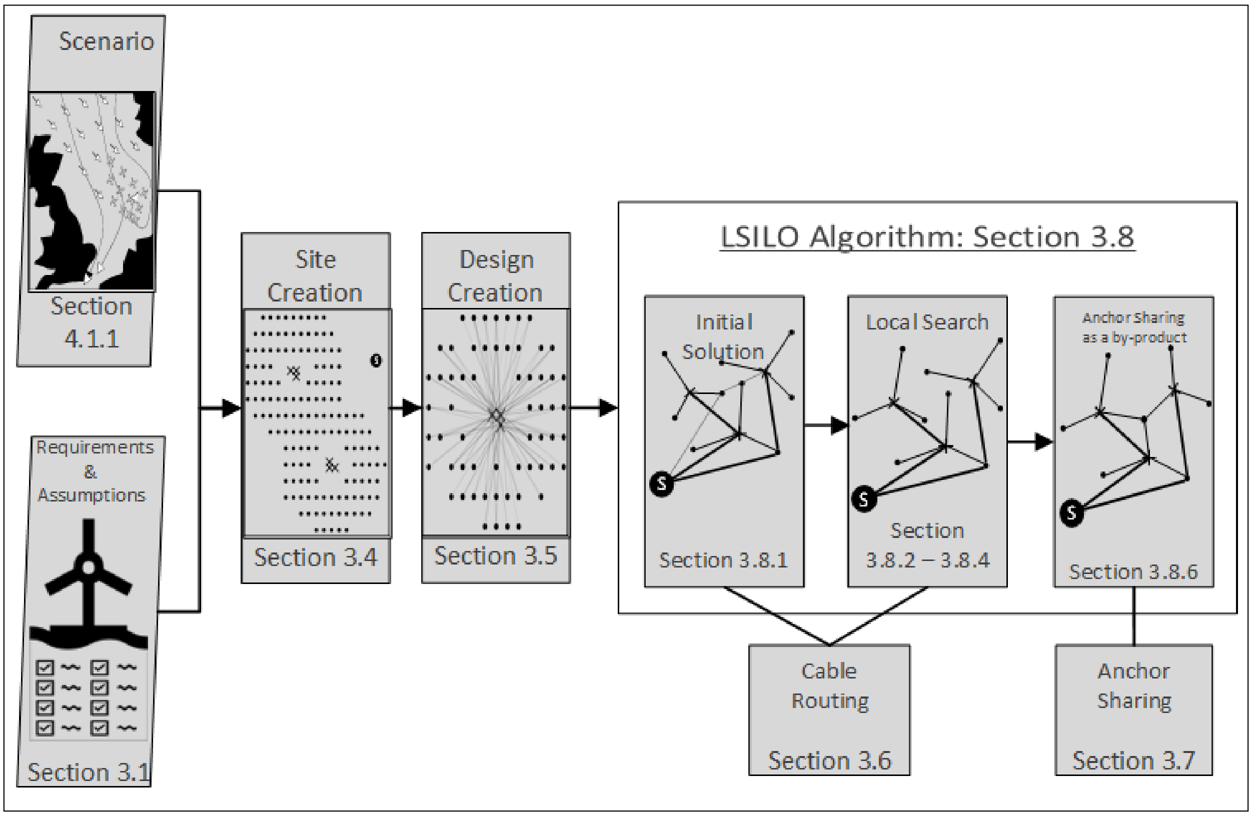


Figure 2: Overview of the algorithm's input and the steps involved in the algorithm.

3.1 Requirements and Assumptions

The following section will present the research-specific requirements and assumptions in developing an algorithm optimising the cable length and anchor structure count of an FOWF. The requirements are derived from designing an FOWF and enforced to keep this study pragmatic and valuable. Conversely, the assumptions are introduced to streamline the problem, minimising unnecessary complexities that might divert attention, thus maintaining a focused and practical approach to the research.

3.1.1 Individual Floating Wind Turbine Design

Requirements Establishing a **minimum and maximum mooring line length** is essential to ensure the structural integrity of the connection between the anchor and the underlying soil. The minimum mooring line length is determined by the minimum pull resistance angle of the anchor [29], and the maximum is enforced to keep the cost manageable and avoid excessive slack, creating uncertainty. Furthermore, to ensure the structural integrity of the turbines, it is critical to have **equal planar angles between mooring lines**. This allows the turbines to withstand wind or wave forces from every direction.

Assumptions Floating offshore wind turbines often spark ideas about actively moving turbines, but for research manageability, the turbines are assumed to be **fixed in their designated positions**.

3.1.2 Site Design

Requirements FOWTs need to have anchors set at a specific angle known as the **mandatory angle** to maintain stability. It is imperative to anchor at least one anchor in the direction of the predominant waves and wind to withstand powerful, persistent directional forces. To design a wind turbine site, **anchor and turbine points are discretised** into a grid structure. This simplifies computational modelling and enables straightforward solution methodologies. Furthermore, discretising the site into a grid-like structure transforms the optimisation problem from a continuous to a discrete problem.

The requirement of discretisation also functions as an assumption, assuming specific locations are allowable while others are disregarded.

Assumptions This research assumes a **uniform seabed**, which limits the scope of research by ignoring site characteristics such as soil conditions and depth in anchor placement. Furthermore, to streamline the study and restrict its focus, the assumption is made that **depth is not a relevant factor**. This assumption will lead to a planar view of the floating wind turbines, reducing design requirements' complexity, such as the cables' floating support mentioned in section 2.1.

Additionally, experts debate whether depth is disadvantageous and suggest that greater depths could benefit costs due to reduced forces on mooring lines [23]. This could lead to the counterintuitive conclusion that an increase in depth would increase the economic value of the site. This research leaves this discussion untouched by assuming the depth is irrelevant.

Additionally, there is considerable debate regarding whether depth is disadvantageous. Some experts argue that greater depths could benefit costs because forces on the mooring lines are reduced . This cost-benefit could lead to the counterintuitive conclusion that an increase in depth would increase the economic value of the site depth. This research leaves this discussion untouched by assuming the depth is irrelevant. Furthermore, this assumption excludes the consideration of obstacles on the seabed, as their inclusion would extend beyond the intended research scope and distract from its primary focus. Another site design assumption is that **no boundary is present**. Boundary constraints can limit many FOWF sites by making it difficult to fit an adequate number of FOWTs. Consequently, this constraint is also sometimes relaxed in industry sites. Assuming no boundaries means anchors can be placed and cables can be routed outside of the site perimeter. However, turbine locations are predetermined input variables within the established boundaries.

Finally, this research assumes **wind characteristics outside the scope** of this research.

3.1.3 Electrical Layout Design

Requirements Standardisation of turbine connections ensures efficient Operation and Maintenance (O&M); **therefore an equal number of turbines are connected to each cable**. In case of a breakdown, quick replacement with a spare cable of equal size leads to cost-effective and straightforward O&M. Unevenly divisible turbine sites can use a smaller cable for the remaining turbines, leading to a remainder lot, a preferred and permitted approach.

Additionally, according to industry experts, **electrical cables cannot cross with each other from a planar point of view** because of safety requirements during installation and maintenance. Also, **electrical cables cannot cross with mooring lines from a planar point of view**. The reasoning is that a disconnected mooring line or electrical cable is more complex, more expensive and less safe to replace when the other mooring line or electrical cable is near it.

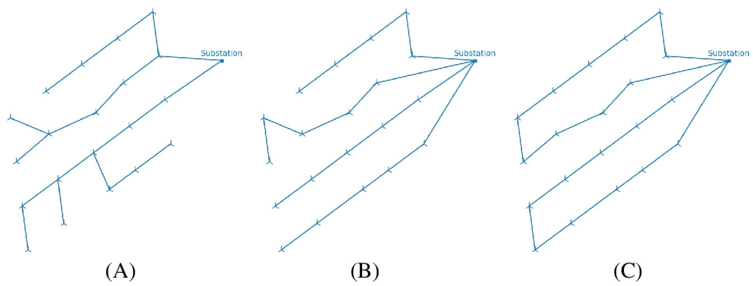


Figure 3: Three main topological configurations concerning inter-array cable layout. A: Branched, B: Radial, C: Looped. Retrieved from [7].

Assumptions The electrical layout design assumes the presence of **only one substation** in the site to avoid the complex turbine partitioning problem [7] since it does not differ significantly from BFOWF cable routing.

Furthermore, the assumption is made that **cable capacity and losses are excluded.** The objective is to ensure physical connectivity without delving into detailed electrical engineering aspects.

To further improve the clarity of this research, every site, regardless of the number of turbines, will assume to have **6 cables** to connect the turbines to the substation. This will improve the reproducibility of the results.

BFOW layout optimization literature identifies different cable routing topologies, such as the branched and looped layouts, as illustrated in figure 3. The branched layout is less preferred due to cable size management complexity, while the looped layout poses significant implementation challenges. As FOWF is a new industry,**a radial layout** is assumed, offering a balance between simplicity and reliability.

3.1.4 Inter-Turbine Design

Requirements To ensure safety and maximize efficiency, wind turbines need to be placed at a specific distance from each other and their anchors. This is dubbed as the **infrastructure free radius**. This requirement is driven not only by safety considerations but also by the need to mitigate wake losses; placing turbines nearby will reduce the efficiency of the wind farm. Furthermore, maintaining a certain distance between anchors is crucial to prevent soil weakening [24].

The second requirement is that **mooring lines of different designs may not overlap**, again in planar view. This requirement is because of safety requirements during O&M and can be attributed to the same reasoning why electrical cables and mooring lines cannot overlap.

3.2 Problem size

Considering a hypothetical floating wind farm comprising 40 turbines, each with a potential of 50 unique design variations. This scenario yields a staggering 50^{40} possible design permutations for the entire farm, illustrating an immense solution space. Such complexity necessitates the application of optimisation techniques such as MILP and other Operations Research (OR) methodologies. Finding a viable and effective design combination within a practical time frame would be impossible without these tools. Moreover, the constraints, as set out in section 3.1, introduce a layer of complexity to this problem. While these constraints inherently reduce the pool of feasible design combinations, they concurrently increase the difficulty of the selection process. These constraints underscore another critical need for sophisticated OR heuristics.

3.3 Scoring

Two measures can be used to evaluate the efficiency of the layouts presented in this research - total cable length in meters and the number of anchors shared. These measures can be taken relative to the site, where the cable length is divided by the site's area, and the amount of anchors shared is divided by the total amount of anchors in the site. A joint measure in the form of NPV is possible but not recommended as it leads to an enigmatic analysis of the two parts of the algorithm.

Measuring the efficiency of the algorithm can be achieved by calculating the cable length, shared anchors, and relating that to the amount of computational time spent in seconds.

In order to safeguard the crossings of electrical cables, a soft constraint is implemented. If there is a crossover, a score of *1e9* is added to the cable length. This score is much greater than any cable length achieved, making it an effective way to identify crossings. The algorithm is designed to avoid long cable lengths, which should also avoid cable crossings.

3.4 Site Creation

This section outlines the methodology used to design the site layout elements of an FOWF. The site layout elements are elements that are site-specific but not turbine-specific. This includes the turbine grid, anchor grid, and substation location. These elements form the foundation for generating FOWT designs and significantly influence the solution space.

The turbine grid will be established first. This grid is a collection of points where an FOWT could be placed on top of the water. This grid might be readily provided in some cases, while in others, a grid might be designed according to specific conditions, such as wave height or ship corridors.

A predetermined number of anchor points, known as the *anchor resolution*, are evenly distributed per axis across the site to establish an anchor grid. To ensure that each turbine grid point is properly surrounded by anchor points, the square defined by the minimum and maximum turbine grid points is widened in the x and y directions. This expansion guarantees that every turbine has a complete range of anchor points surrounding it.

To determine the substation location for site creation, a centrally located substation is preferred to minimise transmission losses and simplify logistics [14]. The average of turbine grid points will be chosen as the substation location.

With the site variables established, the turbine and anchor grid can be combined to identify all possible floating wind turbine designs for individual turbine grid points.

3.5 Design Creation

This subsection explains the methodology used to generate a set of design options from which the algorithm selects. Therefore, this subsection, in combination with the site creation, as explained in section 3.4, defines the solution space in which the algorithm operates. In the context of this research, a design is characterised by a turbine positioned at a turbine grid point, accompanied by a set number of anchors located at anchor grid points, as defined in section 3.4. A mooring line spans between every anchor and its respective turbine grid point, thus making the explicit definition of said mooring line unnecessary. An advantage of decoupling the design creation from the optimisation algorithm is that optimisation can be conducted on diverse sets of designs. This flexibility is crucial as the floating wind industry changes and evolves. Consequently, different assumptions and requirements can be more readily formulated and easily integrated into the algorithm.

3.5.1 Creation of All Viable Design Options

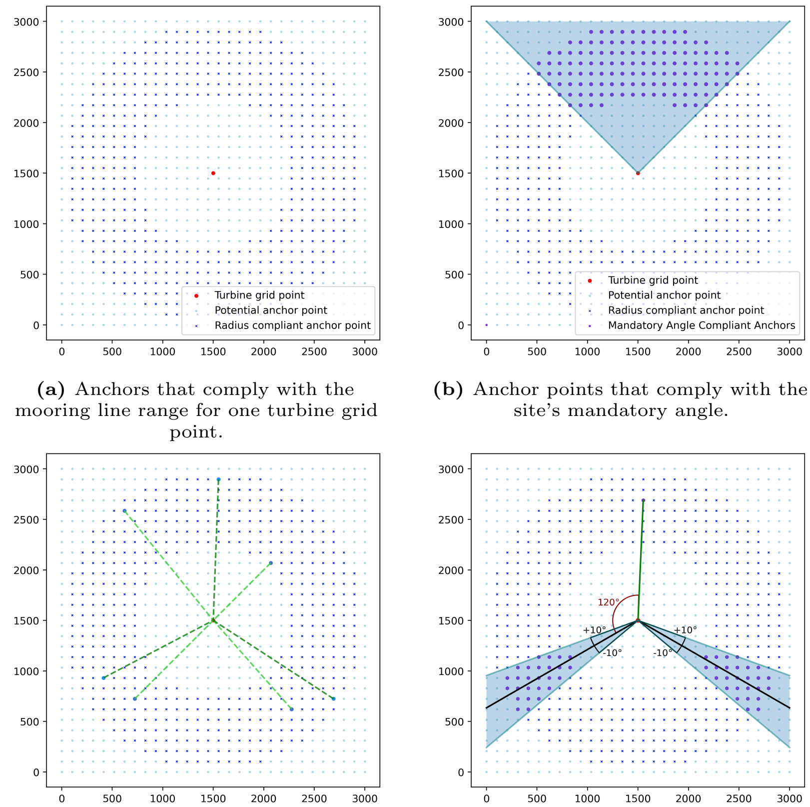
The first step in identifying possible design options for a turbine grid point is to gather all anchor points that fall within the designated range of mooring line distance, as defined in section 3.1.1. A visual representation of this procedure can be found in figure 4a.

Following this, the collected anchor points are evaluated to identify if they comply with the mandatory angle requirement for the site. This angular range remains the same for all turbine grid points within the site. Therefore, each turbine is subjected to an angular filter. Anchor points outside the mandatory angle are only utilized in combination with an anchor point within the mandatory angle. Figure 4b visually represents this process.

Next, the algorithm implements the requirement for equal planar angles between mooring lines, as specified in section 3.1.1. The algorithm must determine the number of mooring lines chosen for each turbine to meet this requirement. figure 4c illustrates this requirement.

To obtain all possible design options, the algorithm considers anchor grid points that comply with the mandatory angle and makes combinations with anchor grid points that fall within the equal angle mooring lines requirement, adding some flexibility to expand the solution space. This step is presented graphically in figure 4d.

Finally, all duplicate design variations are eliminated to produce the final set of viable design options.



(a) Anchors that comply with the mooring line range for one turbine grid point.

(b) Anchor points that comply with the site's mandatory angle.

(c) Two different options: a three-anchor floating turbine or a four-anchor floating turbine.

(d) The anchors viable for combinations because of their presence within the anchor leeway.

Figure 4: Overview of finding all possible viable design options.

3.5.2 Conflicting Designs

Due to the inter-turbine requirements, as explained in section 3.1.4, not all designs can exist in the site simultaneously. The first of the two inter-turbine requirements is that mooring lines of different designs are not allowed to overlap planarly. Two designs sharing turbine grid points within conflicting reach are compared to prevent an overlap. The conflicting reach is two times the maximum mooring line length because, from that point, the mooring lines might influence each other. Now, if the designs contain overlapping mooring lines, after a spacial analysis, both designs are noted as a conflicting pair of designs. The second of the two inter-turbine requirements is that an anchor of one design cannot be too close to the infrastructure of another design. Potential conflicting designs are first identified by checking if the distance between the turbine grid points is within the conflicting reach. If that is the case, the violation is checked by geometrically analysing the two designs on the specified infrastructure-free radius. Two conflicting designs are added to a two-dimensional tuple. The tuple is added to a list of conflicting designs. The algorithm can now only choose one of these designs, never both. A more detailed and mathematical description can be found in the optimisation algorithms throughout this paper, for instance base model 3.1.

It is computationally expensive to compare designs for conflicts by evaluating every design against every other. A more efficient approach could use set theory to streamline this comparison process.

3.6 Cable Routing

This subsection outlines the methodology for efficiently routing cables in floating offshore wind farms, focusing on minimising cable length. Achieving a balance between optimally and speed within the cable routing heuristic is crucial, as it directly impacts the evaluation speed of the different design combinations. A quick cable routing process not only facilitates quicker assessments but also allows for a more significant number of design combinations to be explored. If this exploration can be guided correctly, it can lead to better solutions.

In order to route the cables of an FOWF efficiently and as optimal as possible, recognising the challenges coming with FOWFs is essential. The main challenge originates from the requirement that electrical cables cannot cross mooring lines, mentioned in section 3.1.3. This requirement essentially places many obstacles for the cable to route around. In addition, these obstacles are movable by the algorithm's decision-making. With many movable obstacles in the site, the cable routing differs significantly from traditional cable routing algorithms used in bottom-fixed WFCR.

This large quantity of obstacles makes classical approaches to WFCRs too computationally slow. Therefore, a different approach is needed to route the cables in a timely manner for FOWFs. One initial recommendation for optimising cable routing is to convert each utilised turbine grid point and anchor grid point into nodes, forming a complete graph. A complete graph, as depicted in figure 5a, is a graph where every node is connected to every other node using an edge. These edges will serve as the pathways for the cable routing. Whenever an edge in this complete graph overlaps a mooring line, it shall be removed since it does not comply with the crossing mooring lines requirement, as mentioned in section 3.1.3. Subsequently, a routing algorithm, for instance, A*, could find the shortest path between the turbines that now got disconnected because of the removed edges [19]. This tactic would result in many paths connecting every turbine combination. After analysis of these paths, the shortest total route could be chosen, considering the requirements mentioned in section 3.1.3. Theoretically, this would produce an optimal cable routing for the designs currently employed in the site. However, the practical use would be limited because of the high computational time required to generate this cable routing. In order to quickly assess the designs currently picked on the length of their cable routing, it is important that the cable routing is executed fast.

To efficiently generate a cable routing in a feasible time, such that the resulting routing can be analysed swiftly, the problem is divided into two more manageable subproblems. First, the turbines will be clustered, splitting into smaller groups, making the problem more digestible. These clusters, or as they are called in this research *turbine-groups*, will form the basis for the cable routing. This means that every turbine group will be connected to one cable, and this is the only turbine group this cable connects to. This methodology will be further explained in section 3.6.1. Second, a deeper level is explored, and the question arises of how to effectively route the cables within a group, now clustered together, while minimising the length. This question will be answered in section 3.6.2.

3.6.1 Clustering

This subsection introduces the clustering heuristic based on Cazzaro's clustering heuristic [6]. This heuristic determines which cable connects to which wind turbine in the floating wind farm. The method employed is the so-called 'sweep heuristic'; this heuristic technique is adapted from bottom-fixed wind farm layout optimisation.

As stated in section 3.1.3, an equal number of turbines are required per cable, with a possible 'remainder lot' when the turbines in the site are unevenly divisible. Before beginning to group the turbines, it is necessary to consider a crucial aspect of short cable routing. Namely, the cable does not cover meters in a direction it eventually does not have to go. Therefore, the sweep heuristic is based on an angle-based grouping. The heuristic orders all turbines based on their angles relative to the substation then selects a random starting turbine and groups subsequent ones until each cable has the required number of turbines. This method ensures minimal directional deviation in cable routing. However, since every starting turbine will result in a different clustering (unless no remainder lot is present), this starting turbine's decision heavily influences the algorithm's eventual outcome. Therefore, the algorithm must consider every possible clustering.

3.6.2 Cable Path Selection

Now that the turbines are clustered in groups of a predefined size, the shortest path between turbines must be found to acquire optimal cable routing without losing too much computational time. Maintaining computational speed is crucial, given the frequency of this process in the algorithm. First, the method of finding a feasible path between any two turbines is explained. After that, the procedure for finding the order of connecting any two turbines. Please consider that references to 'two turbine points' in this section also include instances where one of these points is a substation. Since the first connection in every cable is a substation-turbine connection, the substation point does not differ from a turbine point from a cable path perspective.

Feasible Path This subsection focuses on the methodology behind connecting two turbines to achieve a short cable layout efficiently. The challenge resembles the shortest path problem in graph theory; therefore, methods from this operations research section are being borrowed.

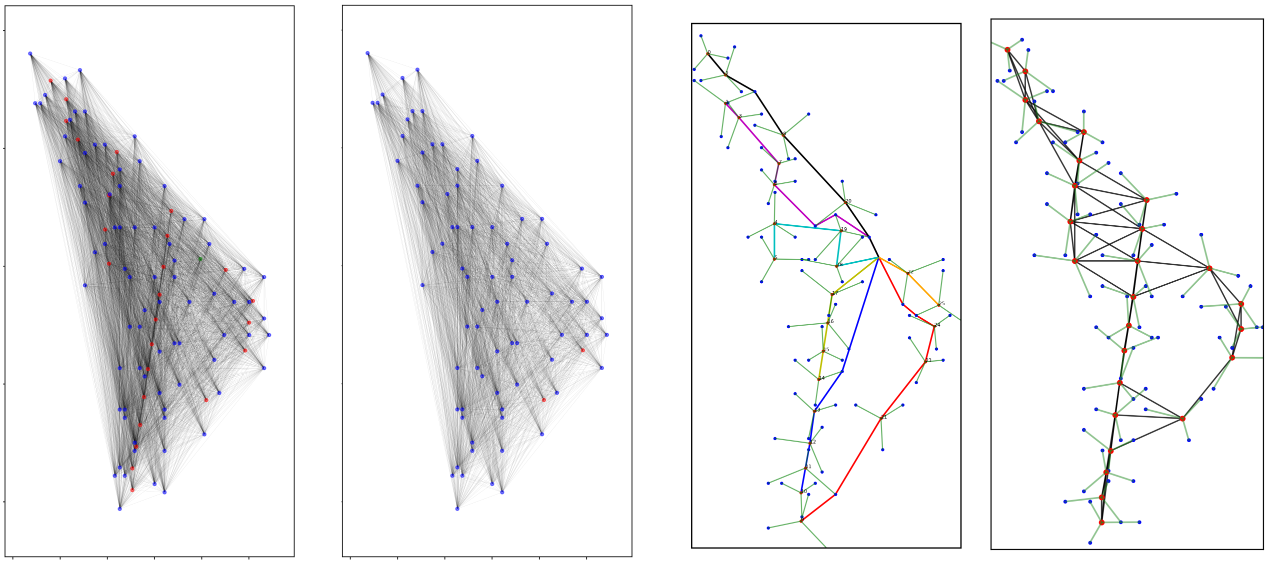
Algorithm 1: Algorithm for constructing cable_route_paths

```
Result: Return cable_route_paths
Data: pairs, CompleteGraph, mooring_line_obstacles
cable_route_paths ← Initialize an empty dictionary;
foreach source, target in pairs do
    Set current source and target in graph CompleteGraph;
    feasible_path ← False;
    // Create a subgraph including only anchors, source, and target
    nodes_to_include ← All anchor nodes in CompleteGraph + source + target;
    Create a subgraph of CompleteGraph with nodes_to_include;
    while not feasible_path do
        path ← Find path from source to target in subgraph using A* with (distance + penalty);
        Assume path is feasible;
        break_statement ← False;
        foreach consecutive pair (node1, node2) in path do
            edge_line ← line between positions of node1 and node2;
            foreach obstacle in mooring_line_obstacles do
                if edge_line intersects obstacle's linestring then
                    Cache edge-design combination;
                    feasible_path ← False;
                    Add penalty to edge in subgraph;
                    break_statement ← True;
                    break;
                end
            end
            if break_statement then break;
        end
        if path is feasible then
            Convert path to edge pairs;
            Append edge pairs to cable_route_path;
        end
    end
    cable_route_paths[source, target] ← cable_route_path;
end
```

To create a feasible cable path between two turbines, it is crucial to follow the requirements outlined in section 3.1. The path must be designed to ensure that electrical cables do not intersect with mooring lines or electrical cables on a planar level. Additionally, a radial cable layout is necessary. It is important to only consider the two turbines in question when formulating the path, avoiding non-radial designs that may result from incorporating other turbines as intermediate steps. Nonetheless, the anchors of other turbines may be included into the paths. Although anchors are not practically used for cable routing, post-processing adjustments can be made to reroute cables around them by a few dozen meters. However, to prevent errors during this step, the path should not be squeezed between two nearby anchors since this would hinder rerouting by a few dozen meters. This constraint is crucial as it connects individual design choices with cable routing ; otherwise, a cable routing could be chosen, and designs could be rotated until fit.

This means that for connecting any two turbines, the complete graph with all designs must be reduced to a subgraph containing only the nodes of the two turbines and all the anchor nodes in the graph. An example of a complete graph using all the designs is given in figure 5a. An example of a valid subgraph used for connecting two turbines is depicted in figure 5b. Please note the two turbines in red. Having defined the relevant subgraph, the next step is constructing the shortest path. Here, the A* algorithm is employed. A* considers the cost of a path, which in this research case is the length of each edge plus a possible penalty, as explained in section 3.3. A substantial penalty is applied to any edge that intersects a mooring line of a design in the site. This penalty effectively disqualifies the edge from being chosen by the A* algorithm.

Given the number of mooring lines and edges within the site, checking every possible combination on



(a) Complete graph. Turbines are displayed in red, anchors are in blue, the substation is in green, and the edges between them are in black.

(b) A subgraph used for connecting two turbines, displayed in red, with each other. The anchors are displayed in blue, and the edges in black.

(c) Example cable routing.

(d) Neighbouring designs, where a black line depicts a neighbouring relationship.

Figure 5: Collection of figures of site *synthetic1*.

crossing each other would be impractical. Therefore, the shortest path is first computed by the A* algorithm (starting with the direct edge connecting the two turbines), and this path is subsequently checked for mooring line intersections. If an intersection is found, the offending edge is penalised, prompting A* to recalculate the shortest path. As such, an iterative setup is used to find the shortest feasible path. Moreover, any edge-design combination that results in a violation is recorded in a data structure used in later parts of the algorithm.

The cable routing algorithm detailed procedure is outlined in pseudocode-style in algorithm 1.

Order Determination The methodology for identifying a feasible path between turbines in a fast way, as detailed in section 3.6.2, leads to the next decision: Determining an adequate order for connecting two turbines within a cluster.

The effective connection order between turbines in a cluster can be determined by considering the distance of the feasible path between them. Starting from the substation, the turbines should be connected in order of the shortest feasible path. The turbine with the shortest feasible path from the substation, would be connected first, followed by the shortest feasible path to this newly connected turbine Equation (1) shows the total number of paths that need to be considered, with n representing the total number of turbines in the turbine group. The shortest feasible path need to be calculated for all pairs within the turbine group. While this method ensures the relative optimal ordering of turbines based on feasible path distances, it can be computationally expensive. To address this, a more efficient approach is proposed where turbines are ordered based on their straight-line distance.

This method was tested using 10,000 turbine groups with randomly selected designs on two sites. Details can be found in appendix A.1. As shown in figure 15, the results demonstrated a substantial consistency between the two methods. The 'Similarity' column in table 1 represents the percentage of the ordering of the straight line method that showed the same results as the ordering of the shortest feasible path method. Specifically, a similarity of 99% for Synthetic1 means that 99% of the time, the ordering of turbines was the same for both the straight-line method and the shortest feasible path method.

This revised approach significantly reduced computational time, detailed in table 1. The time savings increment, especially for larger clusters, such as the *Synthetic3* site, with 30 turbines. This result is logical when realising the number of paths follows quadratic growth as the number of turbines grows because equation (1) could also be written as $\frac{1}{2}n^2 + \frac{1}{2}n$.

This study uses the straight-line distance method for ordering turbine connections since it is almost as accurate as the original but significantly faster.

$$\text{Total Paths} = \frac{n \times (n+1)}{2} \tag{1}$$

Table 1: Time and simularity results between two sites for two different ordering methods. 'Similarity' represents the percentage of identical ordering between the straight line and shortest feasible path methods.

Site	No. of turbines	Avg. time for feasible path [s]	Avg. time for straight line [s]	Avg. time diff. [s]	Similarity (%)
Synthetic1	26	1.028	0.1048	0.9240	99%
Synthetic3	30	2.768	0.5674	2.200	95%

A complete cable routing can now be obtained. An example is given in figure 5c.

Base Model 3.1: Minimise Anchor Structures

Sets:

- I is the set of turbines in the layout.
- T_i is the set of grid points on which turbine i can be placed.
- T is the union of T_i over all $i \in I$.
- D_t is the set of potential designs for turbine grid point $t \in T$.
- D is the union of D_t over all $t \in T$.
- A_d is the set of anchor grid points in design $d \in D$.
- A is the union of A_d over all $d \in D$.
- $C_{d_i d_j}$ or C, is the set of pairs of designs (d_i, d_j) that are conflicting, i.e., cannot coexist.
- Q is the union of all sets $C_{d_i d_j}$, each of which contains a pair of designs that are conflicting.

Decision variables:

- $x_t \in \{0, 1\}$ equals 1 iff turbine grid point t is selected.
- $y_d \in \{0, 1\}$ equals 1 iff design d is selected.
- $z_a \in \{0, 1\}$ equals 1 iff anchor grid point a is selected.

The mathematical model is then given by the following:

$$\text{Minimize} \sum_{a \in A} z_a \tag{obj}$$

$$\sum_{t \in T_i} x_t = 1 \quad \forall \quad i \in I \tag{A1}$$

$$\sum_{d \in D_t} y_d = x_t \quad \forall \quad t \in T \tag{A2}$$

$$y_d \leq z_a \quad \forall \quad a \in A_d, d \in D \tag{A3}$$

$$\sum_{d \in C} y_d \leq 1 \quad \forall \quad C \in Q \tag{A4}$$

The objective function minimises the number of anchor grid points used. Constraint A1 ensures that each turbine is placed, while Constraint A2 guarantees that a single design is chosen for each turbine. Constraint A3 ensures that if a design is selected, the anchors belonging to that design are also selected. Finally, Constraint A4 establishes that no conflicting designs are selected.

3.7 Anchor Sharing

Sharing the anchors to decrease anchoring costs is another goal of this research. Since a *design* has been defined as a turbine grid point with several linked anchor grid points, the goal is to minimise the amount of anchor grid points used. A mathematical model is developed to achieve this goal. Base model 3.1 presents this mathematical model. This mathematical model can now be used to minimise the number of anchors the collection of designs uses by picking designs that share anchors.

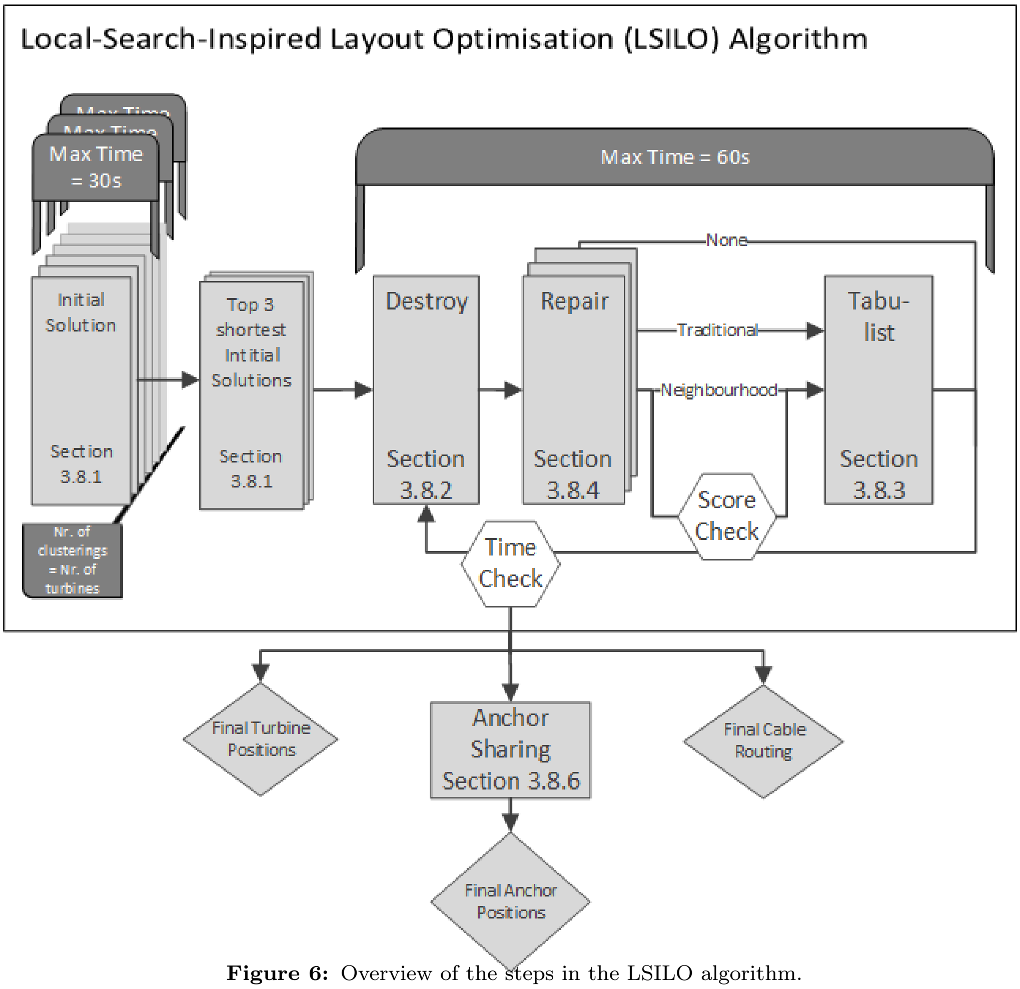


Figure 6: Overview of the steps in the LSILO algorithm.

3.8 Local-Search-Inspired Layout Optimisation

The research goals are combined using a local search algorithm in this study for its quickness and broad and systematic exploration of the solution space [30]. Moreover, a local search focuses on changing only part of the solution and visiting neighbouring solutions. These characteristics are deemed beneficial since oftentimes substantial parts of the solution do not pose any problems and can thus be retained. A tabu search is employed to avoid ending in local optima, which will be explained in greater detail in section 3.8.3 [16].

In the previous subsections, section 3.6 and section 3.7, the methodologies for routing cables and sharing anchors were shared. This subsection explains the LSILO algorithm, which optimises cable routing while allowing anchor sharing. Analysis of the results from section 3.6 and section 3.7 revealed a trade-off; where a layout optimised for anchor sharing is severely limited by the implementation of cable routing, a cable-optimised layout does enable anchor sharing. This observation led to prioritising the optimisation of cable routing in this local search algorithm first and only evaluating the anchor sharing second.

Implementing the local search in this manner is a settlement since anchor sharing will be outside the focus of the optimisation. A comprehensive, combined approach, although better, extends beyond the feasible scope of this research. Nevertheless, future studies might explore more integrated methodologies, where anchor sharing is not just a by-product but a co-optimised objective. More on this in section 5.

Before the local search starts, an initial solution is gained through a weighted optimisation method; this will be further explained in section 3.8.1. After this, the destroy part of the local search will be described in section 3.8.2 and the repair part will be described in section 3.8.4. A tabu list is employed to restrict the local search from revisiting old solutions, which is clarified in section 3.8.3. After this, the methodology behind sharing anchors as a by-product is explained in section 3.8.6.

3.8.1 Initial Solution

The initial solution serves four key purposes. First, since cables are not allowed to cross with each other, as described in section 3.1.3, it will point the local search towards a solution with fewer cable crossings. Second, it increases the diversity of the local search solutions since every iteration of the local search will have a different starting point. Thirdly, it improves the effectiveness of exploring the solution space, pointing the local search towards more promising regions. Finally, it will provide a filter for the number of clusterings in the site; since the amount of clusterings grows with the number of turbines, as mentioned in section 3.6.1, the initial solution orders the clusterings on the most potential.

After a random starting but viable set of designs has been chosen, one for every turbine, the initial solution runs a weighted optimisation. This weighted optimisation tries to minimise the total weights of the designs in the site; a detailed mathematical description can be found in base model 3.2. At the start, every possible design will have a weight of one.

The cable is now routed for one clustering, with several turbine groups, and the cache as described in algorithm 1 is saved. This cache saves the design-edge combinations, leading to an overview of which turbine designs are most in the way due to their higher frequency in the design-edge cache. Therefore, the weights given to the designs are the number of edges they have penalised in the previous cable routings; see section 3.6.2. Now, the weighted optimisation "repicks" the designs, avoiding the designs with a high weight. This loop is repeated for a specific time or until no cable crossings are in the site.

Finally, this procedure is executed for all clusterings in the site, and only the top 3 best initial scores will be transferred towards the local search part of the LSILO algorithm. This shortlist is employed because many clusterings show little potential and a good initial solution has proved to be a good precursor to a good final solution.

It is important to note that while base model 3.2 is capable of running extensively to assign precise weights for every design, this point is not reached in this research. The primary function is to exclude designs that are unfavourable for cable routing swiftly.

Base Model 3.2: Minimise Total Design Weights

Sets:

- I is the set of turbines in the layout.
- T_i is the set of grid points on which turbine i can be placed.
- T is the union of T_i over all $i \in I$.
- D_t is the set of potential designs for turbine grid point $t \in T$.
- D is the union of D_t over all $t \in T$.
- $C_{d_i d_j}$ or C, is the set of pairs of designs (d_i, d_j) that are conflicting, i.e., cannot coexist.
- Q is the union of all sets $C_{d_i d_j}$, each of which contains a pair of designs that are conflicting.
- W_d is the weight of design $d \in D$.

Decision variables:

- $x_t \in \{0, 1\}$ equals 1 iff turbine grid point t is selected.
- $y_d \in \{0, 1\}$ equals 1 iff design d is selected.

The mathematical model is then given by the following:

$$\text{Minimise} \sum_{d \in D} W_d \times y_d \tag{obj}$$

$$\sum_{t \in T_i} x_t = 1 \quad \forall \quad i \in I \tag{B1}$$

$$\sum_{d \in D_t} y_d = x_t \quad \forall \quad t \in T \tag{B2}$$

$$\sum_{d \in C} y_d \leq 1 \quad \forall \quad C \in Q \tag{B3}$$

The objective minimises the total amount of weight in the chosen designs. The first constraint, constraint B1, establishes that each turbine is placed, while constraint B2 secures that a single design is picked for each turbine. Lastly, constraint B3 ensures that no conflicting designs are chosen.

3.8.2 Destroy

The 'destroy' component of the algorithm focuses on removing only part of the solution so that the destroyed part can later be repaired by a (hopefully) better solution. This way, only some of the solution has to be improved at once, and the hope is that the good parts of the solution can be used again. In the case of this research, the destroy will be of a specific size, which will be tuned between 1, 3 and 7, as will be further explained in section 4.1.

To achieve an effective destroy step, a novel technique called *Edge Impact Destroy* (EID) is developed. This technique will consult the previously mentioned design-edge cache, as presented in algorithm 1, and destroy the designs that are most in the way of the current cable routing. The design-edge cache is created during the cable routing and notes every design that destroys a cable edge because the design's mooring line overlaps the specific cable edge. This way, the local search hopes that the repair component of the algorithm repairs the destroyed designs with designs that are less in the way of the cable routing, leading to a lower total cable length. A random destroy technique is developed to assess this technique. Here, the selection of designs to be destroyed in the solution is random. Since this technique is faster than the EID, it can also be better since it can explore a more significant part of the solution space in less time.

Important notes on the specific implementation of these techniques will be presented in section 3.8.3 since it differs per tabu search type.

3.8.3 Tabu search

To refrain the local search from getting trapped in destroying the same designs and to encourage exploration of the solution space, a tabu list is added to the local search. By recording the moves of previous destroy, the algorithm ensures these moves are not repeated until otherwise specified. This improves the algorithm's ability to explore new and potentially more effective solutions. The impact of the tabu search on the algorithm is evaluated by using three different types of tabu searches. Each tabu search method has pros and cons regarding optimising cable routing through a local search within the WFCR of an FOWF.

Traditional The traditional tabu search employs a list of a predefined length, tracking every 'move' that the local search algorithm executed. In this case, a 'move' is a set of designs that were destroyed at the same time. This move can no longer be selected by the algorithm to be destroyed.

In the scenario of a random destroy, a set of designs will be picked from the site using a random sample that is the size of the destroy size. In the case of an EID, the designs selected for destruction have the highest recorded impact on cable routing edges within the site. As stated before, this approach thus prioritises the removal of designs that are most obstructing the cable routing, being a slightly more focused adjustment.

Neighbourhood The neighbourhood approach focuses on explicitly targeting collections of turbines that cause difficulties with cable routing. In an FOWF site, certain parts often cause problems, while others are relatively easy to solve. These problematic parts are referred to as 'neighbourhoods' in this method. In the case of a neighbourhood tabu search, the algorithm tries to solve problem areas and alter the rest of the site around these problem areas. The strategy of this tabu search is marking a solved neighbourhood as 'resolved, restricting changes to it until a turbine neighbouring the 'resolved' neighbourhood is changed. If this happens, the neighbourhood 'resolved' flag is removed, and it is removed from the tabu list. This will cause a re-evaluation of the neighbourhood, which might lead to an improved site. This novel method aims to enhance the efficacy of the local search by concentrating on specific challenging areas, thereby improving the overall cable routing in FOWF.

Determining when turbines are considered neighbours is a fundamental aspect of this approach. In this research, two turbines are neighbours if the inter-turbine distance is less or equal to twice the maximum mooring line distance. This criterion is based on the potential for their impact on cable routing. In figure 5d, an example of neighbouring relations within a site is offered.

This approach modifies the destroy methodology, as mentioned in section 3.8.2. In the case of a random destroy type, the process begins at a randomly selected turbine and extends to a random neighbouring turbine; after this, it extends to a neighbouring turbine of the previous neighbour until the destroy size is met or until no more neighbouring turbines exist. In the case of an EID, the initial choice turbine is the design with the highest edge impact. After this design, the neighbouring design (of the initial design) with the highest edge impact is selected, and this process is repeated until the destroy size is met or until no more neighbouring designs that are not yet planned for a destroy exist.

No Tabu Search Finally, opting not to use a tabu list presents the advantage of computational efficiency. The algorithm can operate at a higher speed without tracking previous destroy moves and finding new ones that do not violate the tabu list. This approach leads to faster solution space exploration, albeit at the risk of potentially revisiting previously explored solutions. Next, the value of implementing a tabu search can be better evaluated by comparing this unrestricted method with the other tabu list options.

3.8.4 Repair

Two repair methods have been developed to repair destroyed designs and decrease cable length within the solution - a random repair and a diversifying repair. For every destruction, a few different repair alternatives are explored. The idea behind this is that it will more quickly find multiple solutions for destroyed areas. An alternative sorter or inexpensive check is developed to sort the alternatives and implement the best one.

Random repair In additive model 3.2a, the model does not seek to optimise any objective. Instead, it attempts to maximise the number of chosen designs, with the limitation imposed by a predefined number set by constraint B2. Consequently, the model's primary goal aligns more closely with solving a feasibility problem: the model aims to identify a feasible set of designs where no conflicting designs are chosen. The model employs an optimisation framework for picking random sets of repair designs. This optimisation framework is inherently deterministic and thus not entirely random. However, it is deemed adequately effective for this research.

Additive Model 3.2a: Select Random Designs

This model is based on base model 3.2.

Sets:

- All sets as defined in base model 3.2, except W_d
- ND is the set of designs $d \in D$ that have not been destroyed in this iterations of this optimisation sequence
- B is the set of designs selected in previous alternatives (Dynamically generated during optimisation).

Decision variables:

- All decision variables as defined in base model 3.2.

The mathematical model is then given by the following:

$$\text{Maximise} \sum_{d \in D} y_d \tag{obj}$$

As described in base model 3.1. (B1 - B3)

$$y_d = 1 \quad \forall \quad d \in ND \tag{B4}$$

$$\sum_{d \in B} y_d \leq (n-1) \text{ (Dynamically added during optimisation)} \tag{B5}$$

The objective function maximises the number of designs on the site; however, constraints B1 and B2 bind this. Constraint B4 establishes that the designs not destroyed in this sequence will be chosen again. Constraint B5 ensures that the same set of designs is only chosen for different alternatives in the same iteration. With three alternatives, the maximum number of B5 constraints is thus 2.

Diversifying repair The destroyed designs are viewed as a geometrical shape for this innovative repair approach. The goal is to achieve a repair where the repair designs are geometrically most diverse with the destroyed designs. The amount of diversity between two designs of the same turbine is noted in a diversity score. In order to calculate the diversity score, a comparison is made between the two designs. First, the designs are overlapped on the coordinate system used, and the closest anchors are linked. Now, the total Euclidean distance between linked anchors determines the diversity score.

The total diversity score is maximised when a destroy size is larger than 1, and thus multiple turbines are involved. The complete mathematical model can be found in additive model 3.2b.

Alternative Sorter Because several alternatives now exist, they must be rated on their performance regarding minimising cable routing. Rerouting the entire site to sort these alternatives on minimal cable length is impossible since that would take too much computational time. However, an inexpensive, partial check could offer a solution. This check will only reroute the edges that the destroyed turbines have impacted; it will do so by replacing them with the repaired turbines for every alternative. The alternatives are then ranked based on the total length of these rerouted connections; a shorter rerouted length indicates a more efficient repair but is not definitive. The alternative yielding the shortest length among the impacted routes is selected as the preferred repair for that scenario. However, it is essential to note that this method focuses solely on the newly impacted routes. As a result, while an alternative may lead to the shortest length in the rerouted section, it does not guarantee the shortest overall cable length across the entire site, as the repair could affect routes that were not part of the initial assessment.

3.8.5 Expensive check

Destroyed designs are replaced with repaired ones, and the full routing will be rerouted. This can lead to an advantageous destroy-repair cycle and a decreased routing length or disadvantageous. In case of an advantageous routing, it is accepted and will become the new routing to beat. In case of a longer cable length, it is discarded. This means that the destroyed neighbourhood is not flagged as resolved for the neighbourhood tabu search and, thus, not added to the tabu list. For the traditional tabu search, the move is always added to the tabu list, regardless of whether an increase in solution is reached.

Additive Model 3.2b: Maximise Diverse Designs

This model is based on base model 3.2.

Sets:

- All sets as defined in base model 3.2, except W_d
- G_d is the diversity score of design $d \in D$
- B is the set of designs that have been destroyed in the previous iterations of this optimisation sequence
- ND is the set of designs that have not been destroyed in this iterations of this optimisation sequence

Decision variables:

- All decision variables as defined in base model 3.2.

The mathematical model is then given by the following:

$$\text{Maximise} \sum_{d \in D} G_d \times y_d \tag{obj}$$

As described in base model 3.1. (B1 - B3)

$$y_d = 1 \quad \forall \quad d \in ND \tag{B4}$$

$$\sum_{d \in B} y_d \leq (n-1) \text{ (Dynamically added during optimisation)} \tag{B5}$$

The objective function maximises the total diversity score in the site. Constraint B4 establishes that the designs not destroyed in this sequence will be chosen again. Constraint B5 ensures that the same set of designs is only chosen once for different alternatives in the same iteration.

3.8.6 Anchor sharing as a by-product

Following the local search presented in section 3.8, the focus shifts towards sharing anchors. Since minimising the routing of cables without crossing obstacles is already a challenging problem, it is decided only to share the anchors that are available for sharing, but not reiterative optimise towards it. We can use the knowledge gained in section 3.7, integrating additional constraints preventing the alteration of the optimised cable routing.

Following the local search presented in section 3.6, the focus shifts towards sharing anchors. Since minimising the routing of cables without crossing obstacles is already a challenging problem, it is decided only to share the anchors that are available for sharing, but not reiterative optimise towards it. We can use the knowledge gained in section 3.5, integrating additional constraints preventing the alteration of the optimised cable routing.

To ensure safety and efficiency, it is important to adhere to the designated grid points for turbines and avoid sharing anchor couples that may cross electrical cables. Careful consideration should be given to selecting anchor points that are compatible with both the turbine and anchor points. Additionally, to prevent rotation and cable crossing, it is recommended to keep at least one anchor point fixed. In order to enforce these constraints, the following methodology is created.

To enforce these constraints, a methodology is proposed. First, shareable anchor pairs are identified, which could use one mutual anchor grid point for multiple anchors. For a pair to have a chance of using a mutual anchor grid point, their distance must be less than twice the difference in distance between the minimum and maximum mooring line length. This way, if two anchors currently employ their turbine's minimum mooring line length, they can still be connected if they find a mutual anchor point within the maximum mooring line length.

Second, the potential pairs found are reviewed, and any pair whose connecting line intersects with an electrical cable is removed from the set. This is because their connection will inevitably make an electrical cable cross a mooring line. Anchors that are being used by the cable routing as corners to turn around will almost always be removed from the list because of this step.

Third, all anchors in the site are evaluated, and any anchor not present in the set of potential anchor pairs is added to the set of fixed anchors. These anchors will be fixed and cannot move in the new solution. Next, every design is checked, and if none of the anchors is fixed, one random anchor will be chosen to be fixed. The fixation of one of the design's anchors restricts the design from moving rotationally and limits the design's mooring lines from rotating into electrical cables.

This approach results in two primary data sets used in the constraints: a set of fixed turbine grid points, which must be used for the designs, and a collection of fixed anchor points. Utilising base model 3.1, the aim is to maximise anchor sharing. However, scenarios may arise where a free anchor is not used for sharing but is still positioned elsewhere after allocation, potentially crossing a cable. Such results can be addressed in post-processing, where anchors are repositioned closer to the turbine grid points until a cable crossing is avoided. The mathematical model and its implications are elaborated in additive model 3.1a

Additive Model 3.1a: Connect Possible Anchors

This model is based on base model 3.1.

Sets:

- All sets as defined in base model 3.1.
- FA_a is the set of fixed anchors $a \in A$, that will remain at the same anchor grid point.
- FTP_T is the set of turbine points $t \in T$ that have been selected and will thus not move.
- d_A is the set of anchors A for each design d.

Decision variables:

- All decision variables as defined in base model 3.1.

The mathematical model is then given by the following:

$$\text{Minimise} \sum_{a \in A} z_a \tag{obj}$$

As described in base model 3.1. (A1 - A4)

$$z_a = 1 \quad \forall \quad a \in FA_a \tag{A5}$$

$$x_t = 1 \quad \forall \quad t \in FTP_t \tag{A6}$$

$$\sum d \in D_A y_d \geq z_a \quad \forall \quad a \in d_A, d \in d_A \tag{A7}$$

The objective minimises the number of total anchor grid points used in the site. Constraint A5 ensures that every fixed anchor will be used and, therefore, selected again. Constraint A6 establishes that the same turbine grid points will be used for the anchor sharing. Finally, constraint A7 safeguards that if a fixed anchor is chosen, a design using this anchor point is also chosen. Preventing it from using the fixed anchor grid point with another design.

4 Results

This section showcases the algorithm's performance, evaluating both total inter-array cable length and computational time, as outlined in section 3.3. The algorithm does not actively work towards anchor sharing, so the metric of shared anchors is not considered a performance parameter, as explained in section 3.8.6.

Starting this section, the experimental setup is outlined in section 4.1, detailing the scenarios that will be tested, the different benchmarking methods and the testing environment. Consequently, section 4.2 presents the numerical results, focusing on the different phases of the LSILO algorithm, as illustrated in figure 6. Finally, section 4.3 discusses the benchmarking results, emphasising the algorithm's relative ability.

4.1 Experimental Set-up

Three main objectives drive this experiment. Firstly, it aims to fine-tune the algorithm's parameters to identify the most effective and best-performing configuration. Secondly, an analysis of specific algorithm components, such as tabu list length and the efficacy of the alternative sorting heuristic, will be used to evaluate their contribution to the algorithm's potential. Thirdly, the results are compared with benchmarking methods, which are newly developed due to the absence of established benchmarks.

Selecting appropriate scenarios is crucial for obtaining meaningful results. The approach includes realistic scenarios provided by the industry partner - Vattenfall - and self-developed circular scenarios. The latter specifically test the algorithm's ability to achieve rational results.

4.1.1 Realistic Scenarios

Vattenfall, the industry partner of this research, provided data on nine synthetic but realistic site scenarios from the BFOWF industry. This study utilises two sets of data: turbine grid points and optimal turbine grid points. The former denotes possible locations for wind turbines from a bottom-fixed viewpoint, while the latter represents the ideal location determined via a BFOWF optimisation process. Wake optimisation is present in these scenarios via this BFOWF optimisation process. The algorithm considers neighbouring grid points of the optimal grid turbine grid point for possible turbine locations, enhancing the solution's flexibility. The scenarios can be found in figure 18, in the appendix, appendix A.4.

In the realistic scenarios provided, the turbine count sometimes exceeds 150. To effectively manage the challenges associated with this amount of turbines in a site, the industry often employs strategies such as turbine partitioning and cluster swapping [6]. However, these strategies do not require significant alteration for floating turbines, making their implementation less relevant to this research. Therefore, it is decided to limit the amount of turbines in the site to a maximum of 30 turbines. This decision aligns with the scale of current floating wind projects [35]. Additionally, the development of larger and more efficient wind turbines in recent years supports the rationale that fewer turbines are necessary to achieve the same power output.

As said before, these realistic scenarios will be used to tune some parameters of the LSILO algorithm to find the best-performing algorithm. The parameters that will be tuned can be found in section 4.1.5.

4.1.2 Circular Scenarios

Circular scenarios will be designed to demonstrate the rationality of the LSILO algorithm. To showcase rational decision-making, the scenarios' symmetry will enable easy analysis by comparing various areas within the same site.

The circular layouts feature a substation situated at the centre of the site, surrounded by several turbines that are evenly distributed. This design facilitates the comparison of cable routings and results in a uniform layout, ensuring that each turbine is equidistant from its neighbouring turbines. In addition to the circular arrangement of turbines across the entire site, the area of influence for floating wind turbines can also be visualised as a circle. The maximum mooring line distance defines the radius of this circle around each turbine grid point.

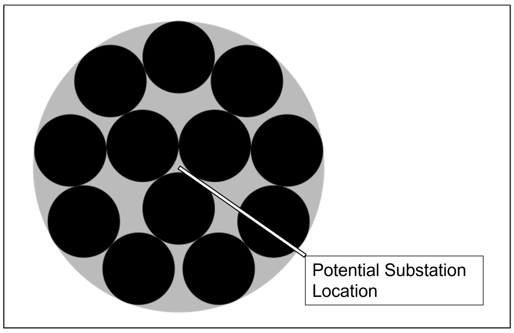


Figure 7: Circle packing in a circle for 12 congruent circles. The outer radius is proven to be around 4.029 times as big as the smaller circles' radii [15]. Figure by [28].

A relevant challenge in this context is the "densest packing of congruent circles in a larger circle" problem, commonly known as circle packing in a circle [18]. This problem addresses the optimal arrangement of congruent circles within a larger circle, as illustrated in figure 7. In the context of this research, the larger circle represents the entire site, while the smaller circles correspond to the influence areas of individual turbines. The solution to this problem provides the minimum outer circle size. This point indicates the moment different turbines' influence areas begin to overlap, making it a relevant threshold for this research.

Different turbine densities can be considered as the large circle's diameter is adjusted and the inner circle's location scaled accordingly. An interesting threshold that will be considered is precisely the minimum outer radius. Also, radii that are 0.75 and 0.5 times the minimum enclosing circle, with turbines and influence areas deliberately overlapping, will be considered.

To further evaluate the rational decision-making of the LSILO algorithm, the number of turbines will be varied to 12, 18, and 30. These specific numbers are chosen for their divisibility by 2 and 3, resulting in more symmetric shapes and creating a space in the middle of the outer radius where the substation can be positioned. This approach yields nine scenarios detailed in appendix A.2.

Table 2: Parameters that will be tuned in this experiment.

Destroy Type	Destroy Size	Repair type	Alternative repeats	tabu search
Random	1	Random	None	None
EdgeImpact	3	Diversifying	3	Traditional
	10		7	Neighbourhood

4.1.3 Site Parameters

The site's characteristics are determined by four parameters. The first parameter is the total number of turbines present on the site. The second parameter is the density of the turbines, which is calculated by dividing the total turbine count by the area surrounding the turbines. This calculation method is easy to understand and efficient, making it simple to replicate research findings. The third parameter measures the maximum number of neighbouring turbines for a single turbine at the site. For an example of neighbouring relationships, see figure 5d. This parameter is designed to showcase the level of congestion in the site. The fourth parameter measures the average number of neighbouring turbines for all turbines present on the site.

4.1.4 Benchmarking Methods

Benchmarking provides a reference point for evaluating the model's performance. Due to the absence of existing research on WFLO of FOWFs, a certain degree of creative thinking is essential to establish a meaningful reference point for the algorithm. This is particularly significant as no benchmark exist in the study's research domain. Therefore, two types of benchmarks will be established, one of which is the rational benchmark provided by the circular scenarios. The other benchmark is a random benchmark, which will be used to evaluate realistic scenarios quantitatively.

Random Benchmark This benchmark will evaluate the LSILO algorithm's ability to exceed an algorithm that randomly selects designs. Since the industry currently relies on randomly picking designs for the layout of FOWFs, this benchmark will be extra interesting. The random benchmark will be created by randomly weighing different designs and then letting the optimisation model, described in base model 3.2, pick a resulting selection of designs. The optimisation model is used because the resulting layout has to be feasible for a fair comparison.

Rational Benchmark For the rational benchmark, circular instances have been created. Here, the key is to check if the model can develop a reasonable cable routing and evident anchor sharing. It is expected that the circular instances show symmetrical cable routings and layouts. Also, the solution quality is expected to deteriorate as the turbine density increases.

4.1.5 Testing Environment

All algorithms referred to in this study are coded in Python, where some graph computations were achieved by implementing the NetworkX package. Optimisation models were built and solved with PuLP, which used COIN-OR as a solver.

The experiment was conducted on the High-Performance Computing (HPC) system at TU Delft, known as DelftBlue [1]. Specifically, each experimental run was allocated one core. The system features a dual Intel XEON E5-6248R with 24 cores each, operating at 3.0GHz. This setup provides a powerful platform for complex computations. Additionally, a maximum of 3GB RAM was made available for each run. Notably, this upper limit was never reached during the experiment, indicating the RAM efficiency of the computational process. Every run was allocated a maximum run time of an hour.

Experimental Parameters The experimental parameters can be divided into two categories. First, the parameters that will be tuned so that the best possible version of the algorithm can be found. These parameters can be found in table 2. However, because of the experiment's size and the research's feasibility, it is impossible to tune every parameter. Therefore, some parameters are being fixed, which can be found in table 3.

Next to these parameters, the anchor resolution was altered for every site such that every turbine had, on average, 60 designs to choose from.

Table 3: Parameters that will be set in this experiment.

Setting	Turbine Cap	No. of Alt. Turbine Locations	Anchor Leeway	Anchor Radius
Unit	[-]	[-]	[degrees]	[meters]
Value	30	3	2	min: 600, max: 1500

Mandatory Angle	Infrastructure Free Radius	No. of Cables	Initial Solution Time Limit	Local Search Time Limit
[degrees]	[meters]	[-]	[seconds]	[seconds]
min: 0, max: 180	50	6	30	60

4.2 Numerical Results

4.2.1 Initial Solution

The initial solution is designed to point the local search towards promising regions, preferably without crossing electrical cables. 2,562 initial solutions have been executed in this experiment, with the time limit set to 30 seconds; the average iteration count of the initial solution was around 1.8 in this 30 second time frame.

66.5% of the initial solutions ended without crossings, deeming the initial solution an effective method for removing crossings from the site. Overall, the sites' initial solution improved the cable length by 1,146,304,486 meters on average. Since a crossing is penalised with a billion meters, it shows that, on average, it solves a crossing every time within the set time limit of 30 seconds. Hinting that it might be beneficial to increase the time limit.

However, in figure 8, it becomes clear that running the initial solution for more iterations does not necessarily improve the number of crossings solved. In figure 9, all scores of a local search iteration are plotted against their initial scores, regardless of improvement. The figure demonstrates that the local search algorithm finds it more challenging to improve solutions with higher initial scores. Therefore, a good initial solution is crucial to solve crossings efficiently.

The correlation between site parameters and algorithm metrics offers insight into how different site factors, as explained in section 4.1.3, influence the initial solution's performance.

The data shows that while there is some correlation between site parameters and algorithmic performance, most are not statistically significant regarding the initial solution. The most notable correlations observed are the solved ratio with the number of turbines and the turbine density. The solved ratio measures the percentage of initial solutions that ended without crossings compared to all initial solutions for a site. The correlation coefficient between the number of turbines and turbine density with the solved ratio is -0.659 and 0.569, respectively. Nonetheless, their p-values (0.0534 and 0.1098) are insignificant at the 0.05 threshold.

These results suggest that while specific site parameters influence the local search, the relationships are complex and not conclusively predictive. However, the result shows that the initial solution offers a good starting point for the local search and sets it up for improvement.

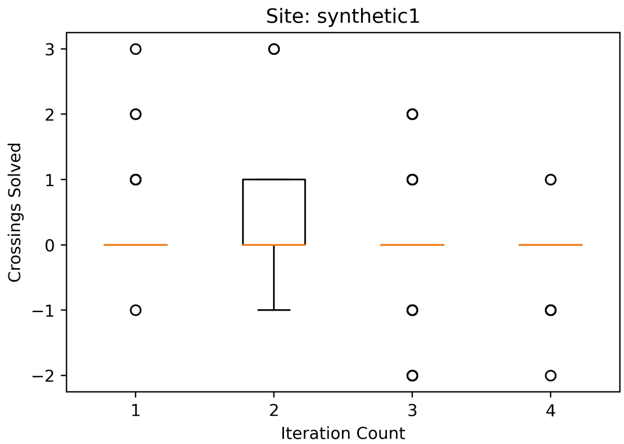


Figure 8: Boxplot showing the number of crossings solved per number of iterations.

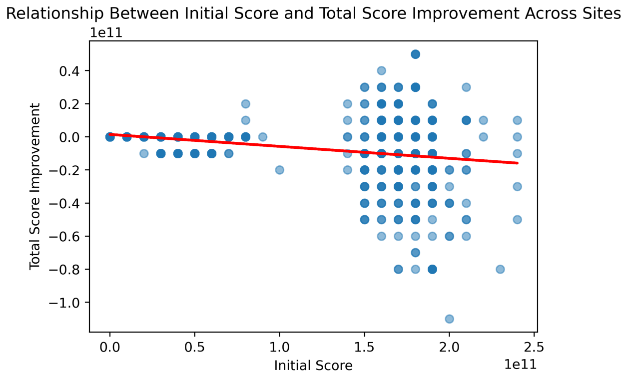
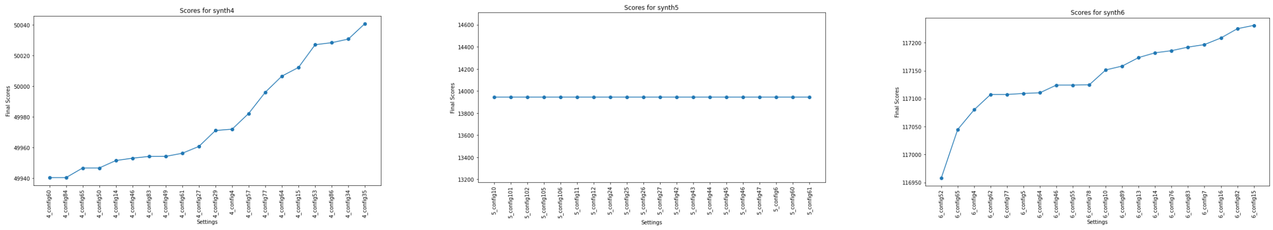


Figure 9: Relationship between initial score and total score improvement.



(a) Result of best scoring configurations of site Synthetic 4. As visible, the top-performing configurations have competing scores with a small variation.

(b) Result of best scoring configurations of site Synthetic 5. The uniformity of the scores across the top 20 configurations suggests a saturation point in optimisation, where each achieves an identical minimal cable length.

(c) Result of best scoring configurations of site Synthetic 6. The graph demonstrates a significant reduction in cable routing for the highest-performing configuration compared to the others.

Figure 10: Comparative overview of the top 20 configurations yielding the lowest cable lengths across three sites. Highlighting the variance in relative performance and underscores that the top-performing configurations are unique to each site, demonstrating the site-specific nature of the parameter-tuning results.

4.2.2 Local Search

Several tests were conducted to analyse the local search part of the LSILO algorithm. First, parameter tuning was executed on multiple parameters of the local search to find the most favourable configuration of parameters for the local search. Following this, the local search results are detailed, and the influence of site parameters is discussed.

Parameter Tuning In the analysis of the parameter tuning section of the experiment, an interesting observation emerges. Surprisingly, no configuration consistently ranks among the top 5 for every site. This result implies that different algorithm configurations yield varying benefits across different sites. Another interesting highlight is observed in site synthetic5's results, depicted in figure 10b. Here, multiple configurations achieve equally low scores, suggesting a potential optimum, likely influenced by the low number of turbines in the site.

A weighted ranking system is introduced to identify the highest-performing configuration across sites despite the lack of top-performing algorithms. Each site's top 20 configurations, based on the shortest cable routing, are assigned points, with the top configuration receiving 20 points. Every rank down receives 1 point less. Summing the points across all sites, three configurations stand out: Configuration 64 (76 points), Configuration 84 (65 points), and Configuration 65 (61 points). These configurations differ across various parameters outlined in table 4.

Analysing the top three local search configurations based on average time to reach optimal scores, Configuration 64 averages 50.3 seconds, Configuration 65 averages 47.0 seconds, and Configuration 84 takes a slightly longer average time of 60.8 seconds.

The impact of the tuned parameters is examined to explore the algorithm's categories in more depth. When looking at table 4 first conclusion can be that a destroy size of 3 with a diversifying repair type proves superior, and using a tabu search, whether traditional or neighbourhood, is compelling.

Comparing tabu search methodologies, figure 11a shows that configurations with a traditional tabu search exhibit a steadier rate of improvement, suggesting a deliberate and consistent exploration for better solutions. The neighbourhood configuration remains closest to the initial level, indicating a less effective but consistent search for improvement.

Upon examining the data on repair repeats illustrated in figure 11b, it becomes apparent that a rise in the number of options results in improved scores at first. However, after three alternatives, the scores level off into a plateau. This implies that an optimal point is achieved when there are approximately three alternatives, although determining the exact location of this plateau would be a interesting area for future research.

In summary, the graph shown in figure 11c indicates that EID is more effective than random destroy. EID achieves a lower score at a faster rate, demonstrating its efficiency. However, random destroy still leads to improvements. It is worth noting that the random destroy process is slower than expected, which suggests that the selection process of random destroy is not as quick as anticipated.

Considering the figures and the faster realisation of the best score, configuration 64 emerges as the optimal choice according to parameter tuning.

Results To achieve the results presented in this section, the nine realistic scenarios were run 100 times using configuration 64 since that is the best-performing configuration.

Table 4: Configuration parameters for the top 3 performing algorithms.

config ID	tabu list	destroy	destroy size	repair	repair repeats	point score
64	Traditional	EdgeImpact	3	Diversifying	1	76
65	Traditional	EdgeImpact	3	Diversifying	3	61
84	Neighbourhood	Random	3	Diversifying	7	65

Table 5: Highlighted correlations between Site Parameters and Local Search Results.

Local Search Result	Site Parameter	Correlation	P-value
Local Search Iteration Count	Number of Turbines	-0.983	1.98e-06
	Largest Nr. of Neighbours	-0.667	0.050
	Avg. Nr. of Neighbours	-0.697	0.037
Total Duration Since Cluster Start	Number of Turbines	0.615	0.078

The outcomes between comparing the site parameters, section 4.1.3, and the performance parameters of the local search are detailed in table 5. The table reveals that the local search iteration count is negatively influenced by the largest and average number of neighbours. It is interesting to note that the total duration since the cluster start has a moderate positive correlation with the average number of neighbours, indicating that sites with more turbines take longer to complete. It is also notable that the neighbour parameters lose statistical significance when considering the overall time analysis, but remain significant at the local search level, suggesting that the initial solution might dilute the neighbouring parameters. The performance parameters, such as cable improvement, do not show any significant differences per site, indicating the agility of the LSILO algorithm.

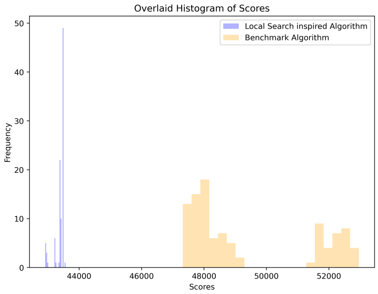
Initial Solution versus Local Search Both the initial solution and the local search part of the algorithm serve their distinct purpose. The initial solution prioritises generating a layout free of crossings and evaluating the different clusterings. In contrast, the local search modifies the turbine and anchor position to generate as little impact as possible on the cable routing. A comparative analysis of these components regarding performance and time gives the following insights. On average, the initial solution takes 31.2 seconds to reduce 0.13 crossings, whereas the local search, with a duration of 63.0 seconds, decreases crossings by only 0.03.

Regarding overall score improvement, excluding the penalty for crossings, the initial solution, on average, adds 60.3 meters to the solution. In comparison, the local search reduces the cable distance by an average of 1390.8 meters. It is important to acknowledge that these algorithm components start from different points and are, therefore, not directly comparable on a one-to-one basis. However, this analysis underscores the unique strengths designed in each component, aligned with their respective goal and aligned to complement each other.

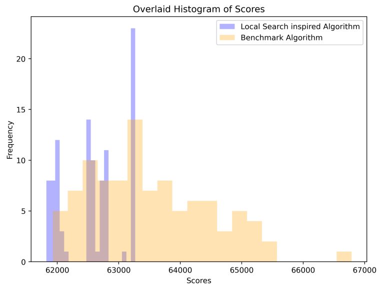
Tabu list length Since the best configuration, configurations 64 (table 4), employs a traditional tabu search, it is of most importance to the algorithm's performance to analyse how the tabu list behaves. The key characteristic of the traditional tabu search is its maximum length, which is the length until it starts removing the oldest moves from the tabu list to free up solution space. The tabu list length balances exploration with exploitation. If this length is too long, too little of the solution space is left open and can be explored by the algorithm. The tabu list cannot correctly deviate from revisiting old solutions if this length is too short. In order to assess if the proper tabu list length is chosen, the tabu list length was analysed on sensitivity. With a too-short tabu list, the algorithm risks revisiting old solutions. However, a too-long tabu list might restrict the solution space search. Therefore, a sensitivity analysis in identifying the optimal tabu list length finds a balance between these two extremes, ensuring a more effective search. This sensitivity analysis aims to find the impact of the tabu list length on solution quality and computational time.

The research adopted a tabu list length of 0.5 times the maximum potential moves. When the maximum limit was reached, and a new move was added, the oldest move was automatically removed from the tabu list. For a fair comparison, all other parameters will be kept constant. All nine scenarios will be tested on five different tabu list lengths: extra short: 0.1, short: 0.25, medium: 0.5, long: 0.75 and extra long: 0.9.

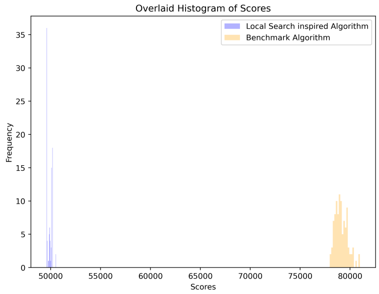
When testing these different tabu list lengths, the following results were found: For the extra long and long tabu list length, the tabu list length was never reached before the algorithm ended. For the medium tabu list length, the maximum length was only reached in site synthetic5, where only seven turbines are present. Regarding all the sites, the 0.5 tabu list length performed best. However, the 0.25 was 8% worse but 13% faster. The 0.1 tabu list length was much faster (22%) but tended to end in local optima, showing a 15% worse performance.



(a) Histogram of site synthetic1.



(b) Histogram of site synthetic2.



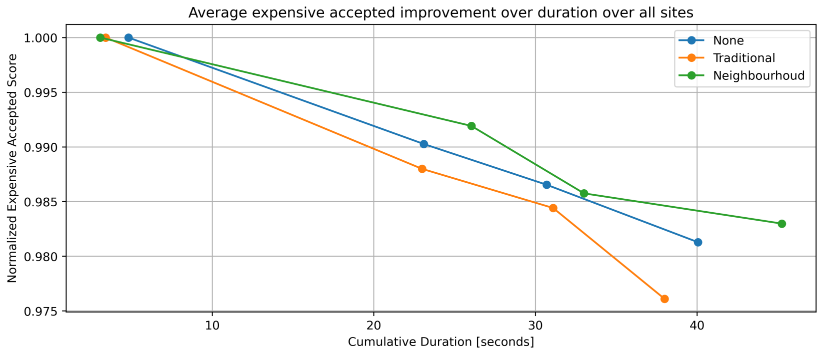
(c) Histogram of site synthetic3.

Figure 13: Histograms comparing results between the random and LSILO algorithm. The bars in orange represent the results from the random algorithm, while the bars in blue represent the results from the LSILO algorithm.

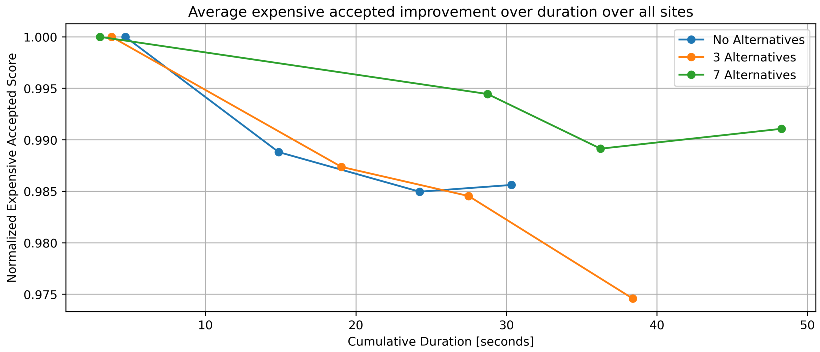
In conclusion, a medium-sized tabu list is the right decision for the researched sites. However, for smaller sites, shorter tabu lists might be beneficial.

4.2.3 Anchor sharing

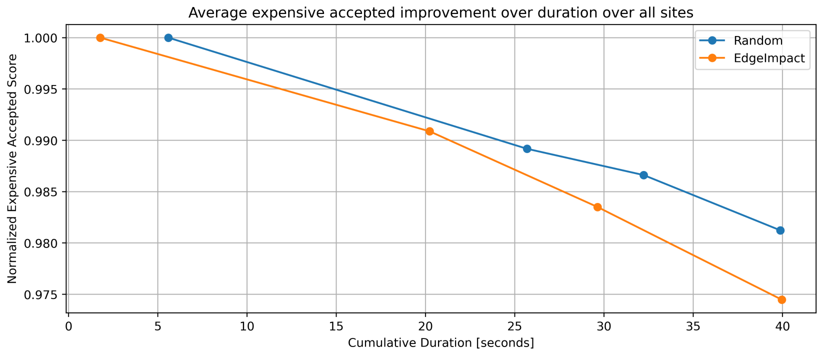
Analysing the anchor-sharing aspect of the algorithm, it was found that in 79.82% of resulting layouts at least some anchors are shared. The percentage of anchors shared can be found in figure 12. The limited sharing of anchors aligns with expectations since the algorithm is not designed to prioritise anchor sharing. Hence, significant outcomes concerning anchor sharing should not be expected. However, some obvious anchors for sharing are not shared. A critical constraint in this manner is freezing one anchor of every design to limit the designs from rotating. This leads to only sharing anchors when the anchors align with the angles of the current designs. This restriction significantly narrows the solution space but is crucial to prevent the mooring lines of changed designs from intersecting with electrical cables. Upon relaxing this rotational constraint, allowing for more design flexibility, there is a noticeable increase in the number of anchors shared, on average 20% more anchors shared. This suggests that while the rotation constraint is essential, it also significantly limits the potential for anchor sharing within the algorithm.



(a) Average expensive accepted improvement over duration over all sites, for tabu searches.



(b) Average expensive accepted improvement over duration over all sites for the different number of alternatives.



(c) Average expensive accepted improvement over duration over all sites for the different destroy types.

Figure 11: Average expensive accepted improvement over all sites for different characteristics of the LSILO algorithm.

Table 6: Improvement of LSILO algorithm over random benchmark.

Site	synthetic1	synthetic2	synthetic3	synthetic4
Without crossing penalty	12.194%	1.478%	36.964%	66.863%

synthetic5	synthetic6	synthetic7	synthetic8	synthetic9
8.121%	0.474%	57.646%	-4.403%	13.563%

4.3 Benchmarks

4.3.1 Realistic instances

In this section, the outcomes of the
random benchmark will be discussed.
This involves comparing the LSILO algorithm's results to those of an algorithm that creates a viable site by randomly selecting designs. A viable site is one that does not have any overlapping mooring lines, but may have crossings of electrical cables. Simply selecting random solutions without crossings would be biased in favor of the random algorithm and would not be a fair comparison. However, if a crossing penalty -of a billion- were imposed, the LSILO algorithm would outperform the random benchmark every time.

Therefore, the crossing penalty is removed from the final results. Since the random benchmark can now employ sites where crossings are allowed, it has an advantage over the LSILO algorithm. Since it is easier to get to short cable routings when crossings are allowed.

Table 6 presents the results of the random benchmark tests as percentage changes. This means that a positive percentage means that the LSILO algorithm had a lower score or shorter cable length than the random algorithm, even though the LSILO avoided cable crossings. Only site synthetic8's random algorithm scored better because it is an easier cable routing when crossings are not penalised. On average, the LSILO algorithm performed 24.05 % better, even though it is not allowed to cross electrical cables, showing the algorithm's performance. Some sites exhibit better scores than others, but an improvement from the industry standard (randomly selecting designs) is clear.

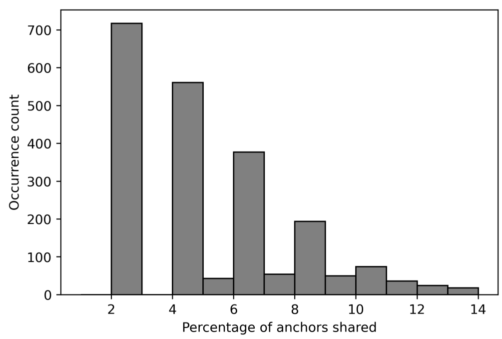


Figure 12: Histogram of the occurrence and the percentages of anchors shared in a resulting layout.
Occurrence

$$\text{Percentage Improvement} = -\left(\frac{\text{LSILO} - \text{Random}}{\text{Random}}\right) \times 100 \tag{2}$$

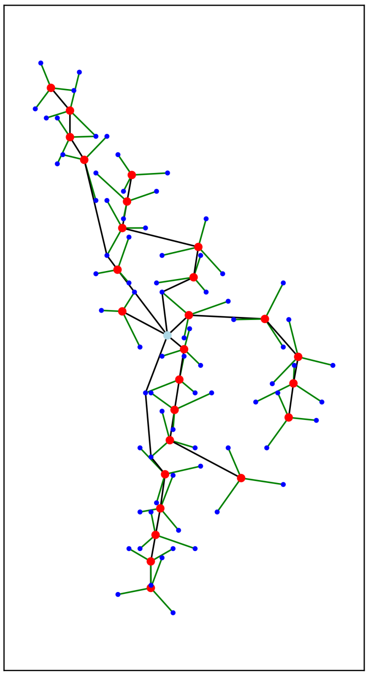
However, merely comparing averages in table 6 may present a skewed image of algorithm performance. The histograms for synthetic1, synthetic2, and synthetic3 indicate better performance of the LSILO algorithm, skewed towards lower scores than the random cases. Additionally, it is noticeable that the frequency of the local search algorithm is often higher, suggesting a propensity to converge into local optima from which it finds escaping challenging. All random benchmarks exhibit a normal distribution, except for figure 13a, which could be attributed to solving for a distinct clustering.

A selection of final layouts is presented in figure 14.

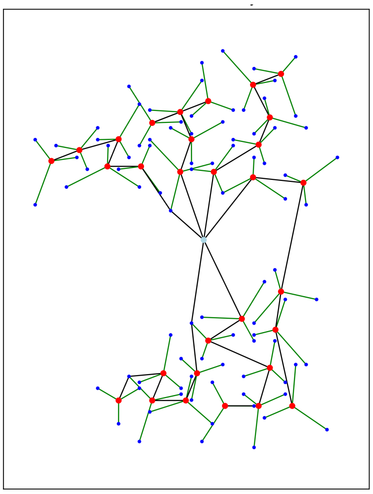
4.3.2 Circular instances

The circular instances will be presented in this subsection of the benchmarking of this research. The results of the circular instances can be found in appendix A.3.

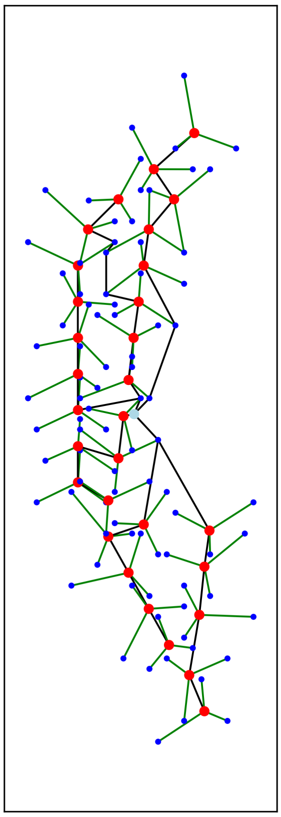
Starting with the 12-turbine sites depicted in the first row of figure 17, it becomes apparent that distributing the six cables symmetrically over the turbines presents a challenge. Figure 17a has more designs in the way of straight routing then figure 17b. In figure 17c, symmetry is far away. Moving to the second row, the 18-turbine sites exhibit greater symmetry, as the cables are more easily divisible. This is particularly noticeable in the densest site where symmetry is successfully maintained. The last row showcases the 30-turbine sites, where symmetry is prominent in lower-density configurations but diminishes as density increases. Notably, instance figure 17h exhibits crossings, and in figure 17i, symmetry is compromised due to increased density. Across all sites, as turbine density increases, achieving symmetry in the (cable) layout becomes more difficult. Across all



(a) Final layout of site synthetic1.



(b) Final layout of site synthetic4.



(c) Final layout of site synthetic9.

Figure 14: A selection of final layouts.

circular instances, the presence of the most shared anchors is consistently observed in medium-density sites, suggesting that turbine density may influence the number of shared anchors.

Upon comparing the performance and site parameters of the circular layouts, several noteworthy observations can be made:

The number of iterations in local search is highly affected by the average and largest number of neighbours, with a strongly negative correlation. A higher turbine density is strongly correlated with longer durations for cheap checks, while a larger number of neighbours is negatively correlated with the duration of expensive checks. The total score improvement and crossings solved do not show significant correlations with site parameters. Lastly, the average number of neighbours has a moderate positive correlation with the total duration since the start of the cluster, suggesting longer durations for sites with more neighbours.

Overall, the number of neighbours (both largest and average) emerges as the most impactful site parameter, demonstrating significant correlations with multiple aspects of local search. While the number of turbines and turbine density also exhibit correlations with certain aspects, their impact is generally less significant.

In conclusion, the circular instances are effectively solved with symmetrical routing up to a certain threshold likely linked to turbine density. Beyond this threshold, the algorithm exhibits errors, resulting in less favourable routings. Further investigation into these thresholds and their implications on algorithmic performance could provide valuable insights for refining the optimisation process in FOWF layout design.

5 Discussion

This study aimed to develop an algorithm that could optimise the layout of an FOWF by minimising inter-array cable length and the number of anchor structures used. However, it was quickly concluded that combining these two goals was challenging and that one goal would be demoted to a sub-goal. It was decided to focus on minimising the cable length since it was more compatible with minimising anchor count. The study investigated different heuristics for cable routing optimisation and anchor sharing - a novel topic in the literature.

A local-search-inspired algorithm was developed, which demonstrated significant improvements over the random-picking technique used in the industry. Over 24% improvement was booked in terms of cable length. This is even more remarkable considering that the benchmark permitted cable crossings, significantly favouring the scores.

Upon analysing the various components of the LSILO algorithm, it was found that the local initial solution was able to resolve 66.5% of the crossings within the designated 30-second timeframe. Notably, it was observed that the time limit was not a hindrance as the number of solved crossings did not increase later on, indicating the initial iterations as most impactful. Consequently, the initial solution demonstrated its value as a strong foundation for the local search part of the LSILO algorithm. The correlation between better initial solution scores and improved final solution scores further supports this assertion.

The parameter tuning process has provided valuable insights into the performance of various components of the local search. A guided exploration of the solution space, utilising the novel heuristics EID and diversifying repair, is more effective than the random approach, which is more haphazard. This comes as no surprise, given the vastness of the solution space. An interesting plateau has also been identified in the number of alternatives, indicating that an optimal alternative count is attained at around three alternatives.

When comparing the impact of the local search part and the initial solution part on the total LSILO algorithm, a complementing relationship is found. While the initial solution resolves more crossings within a given time frame, it does add meters to the routing solution. Conversely, on average, the local search component resolves fewer crossings but decreases the overall meters in the cable routing. These outcomes align with expectations and affirm the successful integration of both components.

Finally, anchor sharing proved possible, as around 80% of the final solutions incorporated shared anchors; however, only a few anchors were shared per solution. This is less than expected but can easily be attributed to the frozen anchor constraint. This constraint limits the designs from rotating, such that it can be ensured that mooring lines of changed designs cross no electrical cables. However, this also means that the design freedom for anchor sharing could be much higher. A possible solution to enhance the ability to share anchors is to integrate them into the local search. For example, after each destruction, a repair move could propose anchor-sharing suggestions that can be accepted or rejected. It would then be necessary to merge the score metrics into a combined NPV.

An interesting, unexpected conclusion is found regarding the site parameters. Namely, the site parameters statistically only influence the time parameters of the algorithm, not the performance parameters of the algorithm. This finding raises the possibility that the site parameters were not chosen appropriately and did not accurately represent the situation. The chosen site parameters focus primarily on the neighbouring designs, as it was believed that the presence of turbines in each other's influence area would have the most significant impact. However, the statistical analysis suggests that this assumption may be incorrect. This could also explain why the traditional tabu search outperforms the neighbourhood tabu search. The latter was designed with the idea that certain congested neighbourhoods required special attention, but the performance parameters indicate this is different.

Nevertheless, when examining the rational layouts, a contradictory conclusion emerges. In these cases, the algorithm's weakness increases as the number of turbines and turbine density increase, leading to less symmetrical designs and local optima. This discrepancy may indicate a more complex relationship between performance and site than this research has uncovered.

The study's findings carry certain limitations that should be considered in practical applications. For instance, the study overlooked significant aspects of the FOWT design by reducing it to just a turbine and three anchors, which could hinder the applicability of the results. Additionally, the implications of these assumptions are unclear and pose a significant challenge to the study's direct practical implications. Nevertheless, the algorithm's adaptability allows it to remain relevant amid the evolving phase of floating wind technology, offering flexibility for potential advancements.

Furthermore, while the study tested the results on nine diverse sites, the turbine count was unbalanced, with 30 turbines being the predominant figure. However, the study is practical for the industry as it constructed a skeleton for future research, pointing in promising directions.

The study needed help finding quality benchmarks and used a random benchmarking technique. Although valid, the analysis is not one-to-one because of the electrical crossings. Therefore, the study advocates for using its publicly available data and results as a new benchmark to standardise benchmarking and increase the quality of future studies. The circular benchmark proved to be useful, but quantitative backing was lacking.

The development and analysis of this algorithm provide new insight into the pitfalls in further developing FOWF layout optimisation. Starting with generating many designs upfront initiated some issues, such as generating all conflicting designs and stiffness in anchor sharing, which resulted in non-shared anchors where anchors could be shared. Nevertheless, with the execution of this study, a benchmark has been established, paving the way for further research on this topic.

6 Conclusion and Future Work

This research developed a practical algorithm for optimising the inter-array cable length of an FOWF while also allowing for anchor sharing, to research the ability to optimise layout configuration for FOWF. The algorithm is designed to offer insights into the challenges and pitfalls involved in developing this research area. The study achieves this by developing a cable routing heuristic, an anchor sharing heuristic, an initial solution algorithm, and a novel local-search-inspired algorithm to combine these computational models into an efficient and performing algorithm.

The first conclusion regarding the local-search-inspired algorithm, is that it effectively minimises inter-array cable length while also allowing for anchor sharing. On average sharing anchors in 80% of the final solutions, and improving the benchmark values by 24%. This is even more remarkable considering that the benchmark allowed for electrical cable crossings, where the LSILO avoided them. Furthermore, the execution time of the local-search-inspired algorithm is limited to an equitable 90 seconds, indicating the time-efficient exploration of the solution search.

The initial solution algorithm complements the local search part, with the initial solution solving 0.13 crossings and adding meters, while the local search only solves 0.03 crossings but reduces the cable distance by an average of 1390.8 meters. The initial solution's time frame of 30 seconds is sufficient for the sites tested, as most crossings are solved in the first iterations.

When diving deeper into the local search part of the algorithm, the study shows that the ideal destroy size for the tested sites is three turbines, and the best-performing destroy type compared to the time taken is the self-developed heuristic EID. The ideal repair strategy is a diversifying repair, showing that the steered, novel heuristics outperform the random heuristics. However, the performance of the repair plateau around three for the sites tested in this research. The exact location of this plateau and the influence of site parameters on its location could be interesting lines of future work.

In the domain of tabu search heuristics, the study observes that a traditional tabu search exhibits superior time efficiency and performance compared to the neighbourhood tabu search. As expected, not using a tabu search is inferior to using a tabu search. With a tabu list length of 0.5, the potential moves performed best but executed slower. A length of 0.25 was 8% slower but 13% faster. A tabu list of length 0.1 times the potential moves was 22% quicker but showed a 15% worse performance on cable length. However, a smaller tabu list size might work advantageous for smaller sites since time is less relevant.

Furthermore, the circular benchmark showcased that the LSILO algorithm achieved rational results until a specific turbine density. Next, the algorithm performed better and more consistently when the site layout was more symmetrical. A suggestion for future work could be analysing this threshold of turbine density when the performance deteriorates.

Fourth, the strong negative correlation between local search iteration count and the number of neighbours suggests that higher neighbour density facilitates quicker convergence than lower neighbour density sites. However, it is interesting that no performance parameters show correlations with the chosen site parameters, suggesting that future research could include an analysis of different site parameters.

Finally, anchor sharing was achieved, but to a lesser extent than expected. Reasons for this could be the severely limited freedom. An interesting idea for future work could be to find an implementation where the final anchor sharing is less constrained. Another implementation might be to include the anchor sharing into the repair part of the LSILO.

Although the limitations of the algorithm may initially appear to hinder its practical application, its design allows for adaptability. This means that the algorithm can remain in its current limited form, while also being easily extended to achieve practical results. Many of the constraints and challenges associated with practically implementing this algorithm can be addressed by borrowing techniques of the bottom-fixed optimization industry.

Other avenues for future research include a better time analysis, where the main focus could be on how long it takes to run which part of the algorithm for which kind of site. Regarding sites, the research focused on realistic and manageable sites; however, another interesting future work could be pushing the algorithm more to find its plateaus. In this research, LSILO could only not solve crossings in synthetic8, and in the circular instances, only the last two of the algorithms started to struggle. An obvious suggestion for future work could be to combine anchor sharing and cable routing more inherently. A starting point for this research could be to combine the objectives into a cost value, which can then be optimised. After that, deciding for every anchor share if it is worth a cable reroute. Next, a study into finding the conflicting design combinations faster is also interesting since this now needs to be done as a preprocessing step.

Synthesising this, the development of a layout algorithm for an FOWF presents an intriguing research opportunity that warrants further exploration. However, this area of study poses several challenges and obstacles, particularly in balancing the competing goals of anchor sharing and cable routing. This research has discovered a method for effectively routing cables in a site with obstacles and has determined that anchor sharing is only possible after cable routing, albeit with significant limitations. To achieve optimal results for both cable routing and anchor sharing, it is advisable to approach the problem from a different perspective, such as considering dual anchor sharing and determining whether synthesising anchor combinations, connecting them, or leaving them open for cable routing is worthwhile after every repair move. This approach may involve utilising cost-effective checks or alternative order heuristics, as outlined in this research, and combining performance parameters into a single cost parameter.

References

[1] Delft High Performance Computing Centre (DHPC). *DelftBlue Supercomputer (Phase 1)*. https://www.tudelft.nl/dhpc/ark:/44463/DelftBluePhase1. 2023.

[2] Adesoji Adelaja et al. "Assessing offshore wind potential". In: *Energy Policy* 42 (2012), pp. 191–200.

[3] Tze-Zhang Ang et al. "A comprehensive study of renewable energy sources: Classifications, challenges and suggestions". In: *Energy Strategy Reviews* 43 (2022), p. 100939. ISSN: 2211-467X. DOI: https://doi.org/10.1016/j.esr.2022.100939. URL: https://www.sciencedirect.com/science/article/pii/S2211467X2200133X.

[4] Philipp Beiter et al. *The cost of floating offshore wind energy in California between 2019 and 2032*. Tech. rep. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2020.

[5] Dilara Gulcin Caglayan et al. "The techno-economic potential of offshore wind energy with optimized future turbine designs in Europe". In: *Applied energy* 255 (2019), p. 113794.

[6] Davide Cazzaro, Martina Fischetti, and Matteo Fischetti. "Heuristic algorithms for the wind farm cable routing problem". In: *Applied Energy* 278 (2020), p. 115617.

[7] Davide Cazzaro, David Franz Koza, and David Pisinger. "Balanced and unbalanced networks in offshore wind farms". In: *11th Triennial Symposium on Transportation Analysis conference*. 2022.

[8] Davide Cazzaro and David Pisinger. "Variable neighborhood search for large offshore wind farm layout optimization". In: *Computers & Operations Research* 138 (2022), p. 105588.

[9] Patrick Connolly and Matthew Hall. "Comparison of pilot-scale floating offshore wind farms with shared moorings". In: *Ocean Engineering* 171 (2019), pp. 172–180.

[10] Michael C. Devin et al. "Optimizing the Cost and Reliability of Shared Anchors in an Array of Floating Offshore Wind Turbines". In: *ASCE-ASME J Risk and Uncert in Engrg Sys Part B Mech Engrg* 7.4 (Aug. 2021), p. 040905. ISSN: 2332-9017. DOI: 10.1115/1.4051163. eprint: https://asmedigitalcollection.asme.org/risk/article-pdf/7/4/040905/6802862/risk_007_04_040905.pdf. URL: https://doi.org/10.1115/1.4051163.

[11] H Díaz, RB Fonseca, and C Guedes Soares. *Site selection process for floating offshore wind farms in Madeira Islands*. 2019.

[12] Katherine Dykes. "Optimization of wind farm design for objectives beyond LCOE". In: *Journal of Physics: Conference Series*. Vol. 1618. 4. IOP Publishing. 2020, p. 042039.

[13] *Ecological effects of floating offshore wind (ECOFLOW)*. https://www.ukri.org/what-we-do/browse-our-areas-of-investment-and-support/ecological-effects-of-floating-offshore-wind-ecoflow/. Accessed: Jan. 5, 2024.

[14] Chakib El Mokhi and Adnane Addaim. "Optimal Substation Location Of A Wind Farm Using Different Metaheuristic Algorithms". In: *2020 IEEE 6th International Conference on Optimization and Applications (ICOA)*. 2020, pp. 1–6. DOI: 10.1109/ICOA49421.2020.9094469.

[15] Ferenc Fodor. "The densest packing of 12 congruent circles in a circle." eng. In: *Beiträge zur Algebra und Geometrie* 41.2 (2000), pp. 401–409. URL: http://eudml.org/doc/231828.

[16] Fred Glover. "Tabu search—part II". In: *ORSA Journal on computing* 2.1 (1990), pp. 4–32.

[17] S.A. Grady, M.Y. Hussaini, and M.M. Abdullah. "Placement of wind turbines using genetic algorithms". In: *Renewable Energy* 30.2 (2005), pp. 259–270. ISSN: 0960-1481. DOI: https://doi.org/10.1016/j.renene.2004.05.007. URL: https://www.sciencedirect.com/science/article/pii/S0960148104001867.

[18] R.L. Graham et al. "Dense packings of congruent circles in a circle". In: *Discrete Mathematics* 181.1 (1998), pp. 139–154. ISSN: 0012-365X. DOI: https://doi.org/10.1016/S0012-365X(97)00050-2. URL: https://www.sciencedirect.com/science/article/pii/S0012365X97000502.

[19] Peter E Hart, Nils J Nilsson, and Bertram Raphael. "A formal basis for the heuristic determination of minimum cost paths". In: *IEEE transactions on Systems Science and Cybernetics* 4.2 (1968), pp. 100–107.

[20] John K Kaldellis et al. "Environmental and social footprint of offshore wind energy. Comparison with onshore counterpart". In: *Renewable Energy* 92 (2016), pp. 543–556.

[21] A. Martinez and G. Iglesias. "Mapping of the levelised cost of energy for floating offshore wind in the European Atlantic". In: *Renewable and Sustainable Energy Reviews* 154 (2022), p. 111889. ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2021.111889. URL: https://www.sciencedirect.com/science/article/pii/S1364032121011564.

[22] Seiied Mohsen Masoudi and Mehdi Baneshi. "Layout optimization of a wind farm considering grids of various resolutions, wake effect, and realistic wind speed and wind direction data: A techno-economic assessment". In: *Energy* (2022).

[23] Karl Meyer. *Personal Communication.* Personal interview. System Design Engineer at Vattenfall. Discussion on the scale of current floating wind projects. Jan. 2024.

[24] Matin Jalali Moghadam et al. "Experimental study on the performance of plate anchor retaining walls". In: *International Journal of Physical Modelling in Geotechnics* 19.3 (2019), pp. 128–140.

[25] G. Mosetti, C. Poloni, and B. Diviacco. "Optimization of wind turbine positioning in large windfarms by means of a genetic algorithm". In: *Journal of Wind Engineering and Industrial Aerodynamics* 51.1 (1994), pp. 105–116. ISSN: 0167-6105. DOI: https://doi.org/10.1016/0167-6105(94)90080-9. URL: https://www.sciencedirect.com/science/article/pii/0167610594900809.

[26] Walt Musial. *Overview of floating offshore wind (text version).* Feb. 2020. URL: https://www.nrel.gov/news/video/overview-of-floating-offshore-wind-text.html.

[27] Nicolai Gayle Nygaard and Sidse Damgaard Hansen. "Wake effects between two neighbouring wind farms". In: *Journal of Physics: Conference Series.* Vol. 753. 3. IOP Publishing. 2016, p. 032020.

[28] Patrick87. *Circle Packing Image.* https://commons.wikimedia.org/w/index.php?curid=27447118. Public Domain. June 2013.

[29] T.E. Schelfn and C. Östergaard. "The vessel in port: Mooring problems". In: *Marine Structures* 8.5 (1995). Moored and Tethered Structures, pp. 451–479. ISSN: 0951-8339. DOI: 10.1016/0951-8339(95)97304-Q. URL: https://commons.wikimedia.org/w/index.php?curid=27447118.

[30] Dale Schuurmans and Finnegan Southey. "Local search characteristics of incomplete SAT procedures". In: *Artificial Intelligence* 132.2 (2001), pp. 121–150.

[31] V Sykes, M Collu, and A Coraddu. "A review and analysis of the uncertainty within cost models for floating offshore wind farms". In: *Renewable and Sustainable Energy Reviews* 186 (2023), p. 113634.

[32] Ryota Taninoki et al. "Dynamic cable system for floating offshore wind power generation". In: *SEI Technical review* 84.53-58 (2017), p. 146.

[33] Xinbao Wang et al. "A review of aerodynamic and wake characteristics of floating offshore wind turbines". In: *Renewable and Sustainable Energy Reviews* 175 (2023), p. 113144.

[34] Simon Watson et al. "Future emerging technologies in the wind power sector: A European perspective". In: *Renewable and sustainable energy reviews* 113 (2019), p. 109270.

[35] Noah Woning. *Personal Communication.* Personal interview. System Design Engineer at Vattenfall. Discussion on the scale of current floating wind projects. Jan. 2024.

[36] Yan Wu et al. "A design methodology for wind farm layout considering cable routing and economic benefit based on genetic algorithm and GeoSteiner". In: *Renewable Energy* 146 (2020), pp. 687–698.

[37] Kiyotomo Yagihashi et al. "Dynamic cable installation for Fukushima floating offshore wind farm demonstration project". In: *Proceeding Jicable.* 2015.

[38] Peng-Yeng Yin and Tai-Yuan Wang. "A GRASP-VNS algorithm for optimal wind-turbine placement in wind farms". In: *Renewable Energy* 48 (2012), pp. 489–498. ISSN: 0960-1481. DOI: https://doi.org/10.1016/j.renene.2012.05.020. URL: https://www.sciencedirect.com/science/article/pii/S096014811200345X.

[39] Rune Yttervik. "Hywind Scotland–status and plans". In: *EERA DeepWind* (2015).

A Appendix

A.1 Straight Line Experiment

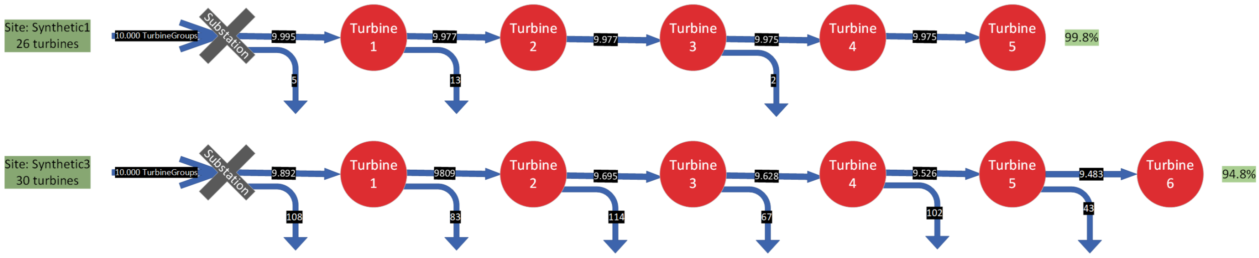


Figure 15: Experiment where the straight line distance ordering is compared against the shortest path ordering.

A.2 Circular Scenarios Set-up

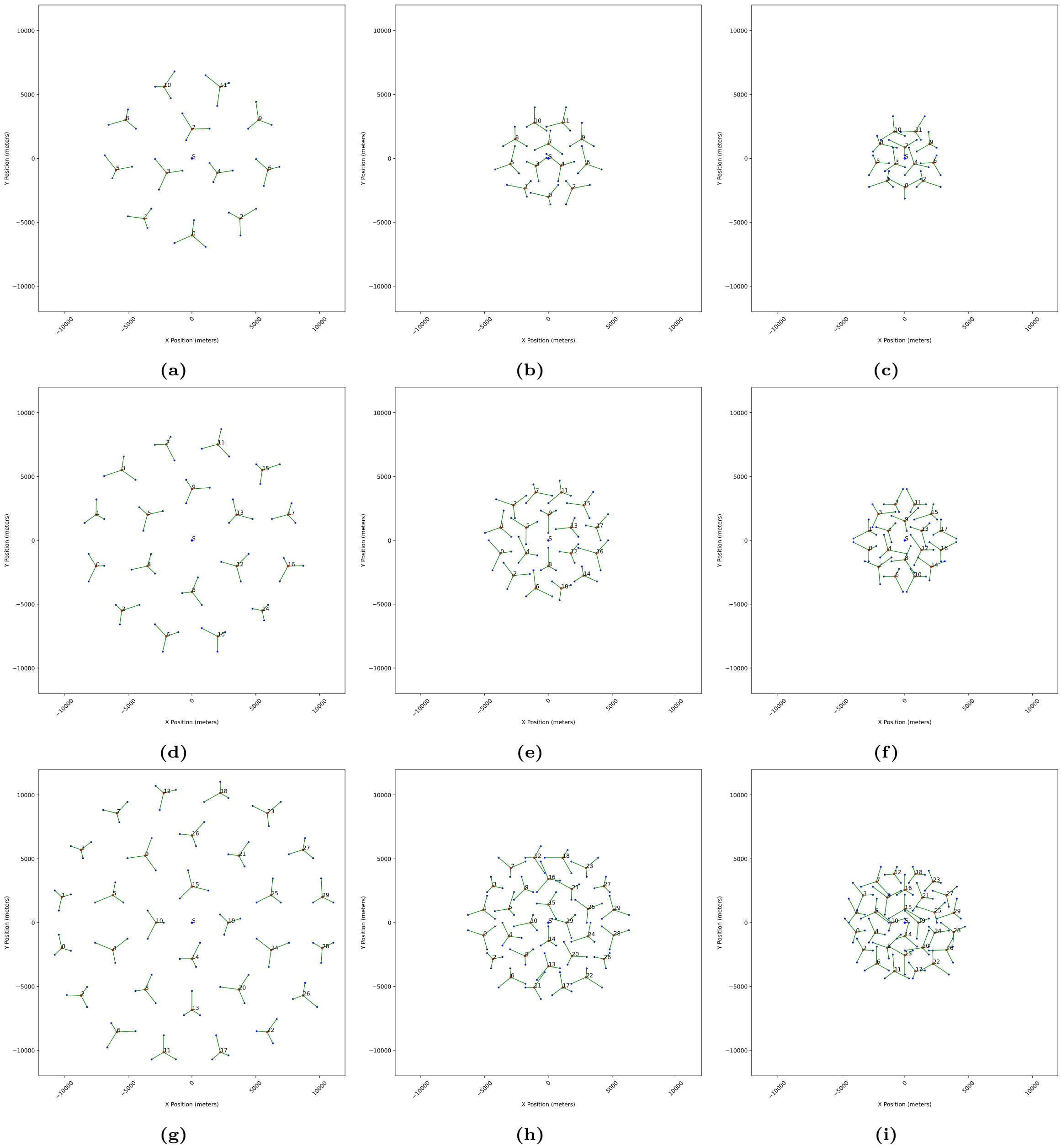


Figure 16: Overview of the circular instances

A.3 Circular Scenarios Results

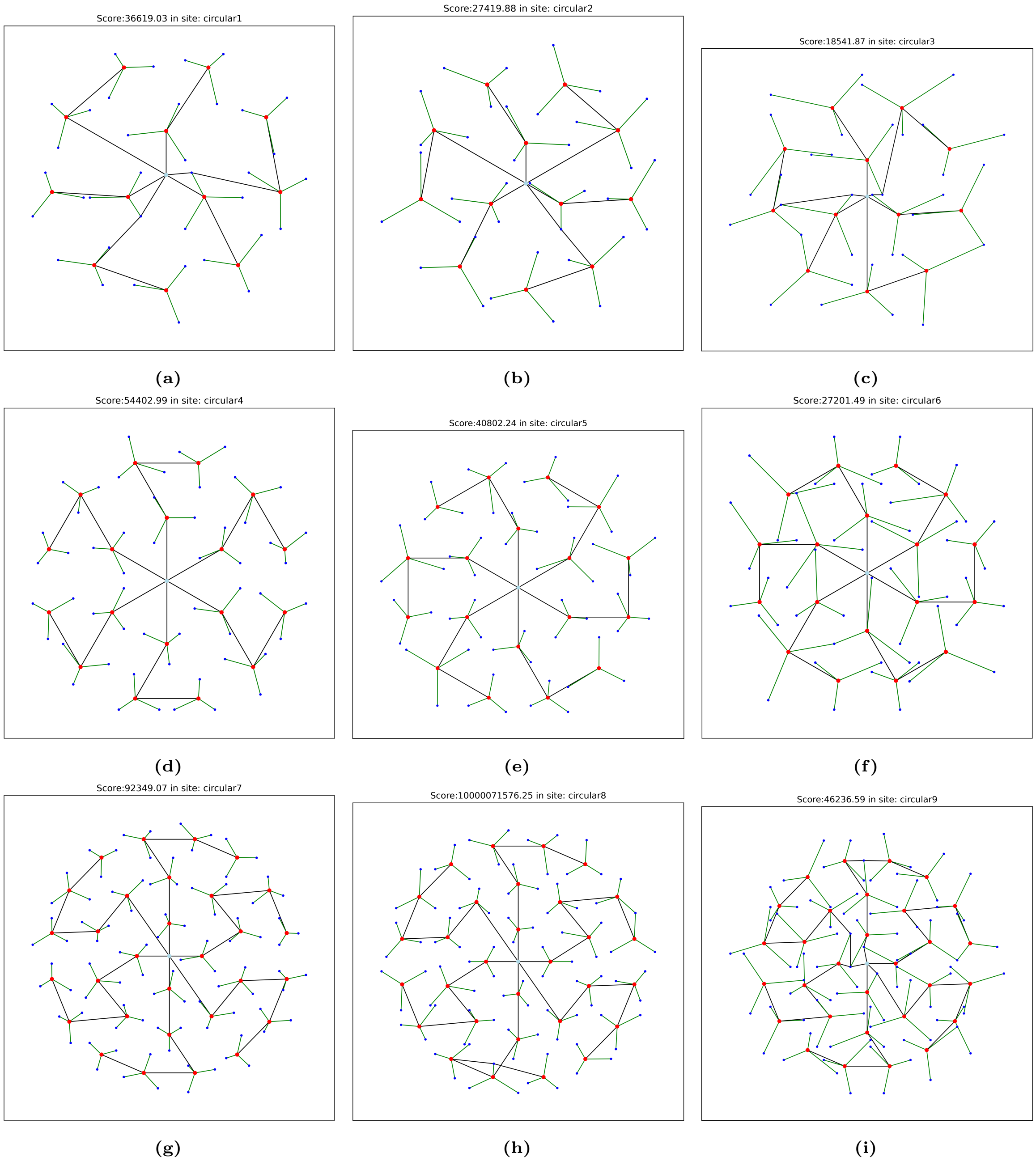
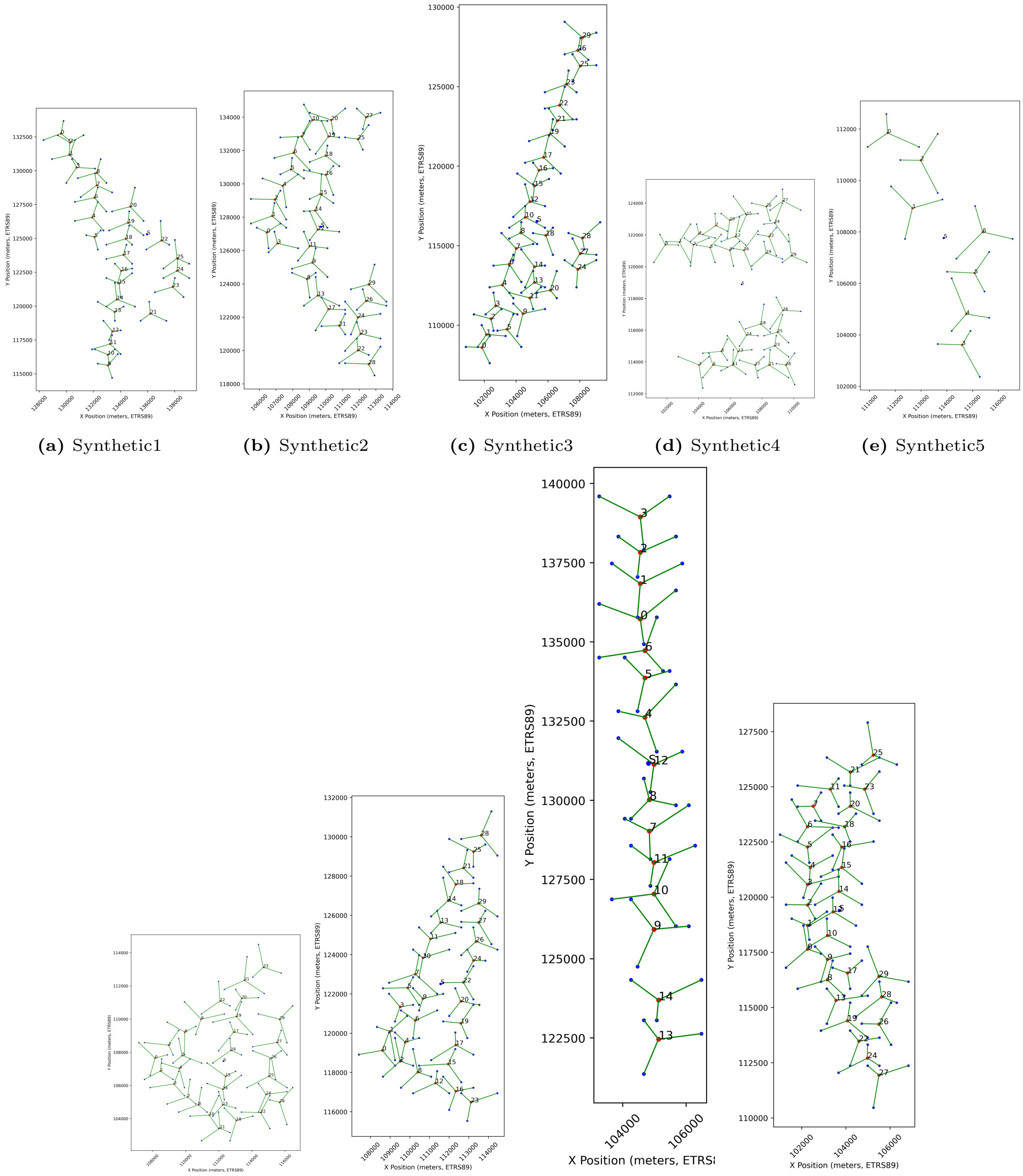


Figure 17: Overview of the solved circular instances.

A.4 Synthetic Scenarios Set-up



(a) Synthetic1 **(b)** Synthetic2 **(c)** Synthetic3 **(d)** Synthetic4 **(e)** Synthetic5

(f) Synthetic6 **(g)** Synthetic7 **(h)** Synthetic8 **(i)** Synthetic9

Figure 18: Overview of the synthetic instances.

Part II

Literature Review

*This part has been assessed for the course AE4020 Literature Study.

Lay-out Optimisation of Floating Offshore Wind Farms

A literature review

AE4020: Literature Study

Steyn Janus

Delft University of Technology

TU Delft

Lay-out Optimisation of Floating Offshore Wind Farms

A literature review

by

Steyn Janus

Student Name	Student Number
Steyn Janus	4566351

In collaboration with Vattenfall.

TU Delft Supervisor: Dr. A. Bombelli
Company Supervisors: Dr. M. Kidd & Dr. D. Koza
Faculty: Faculty of Aerospace Engineering, Delft

Cover: Two floating offshore wind turbines at the demonstration project ”Erebus” in the Celtic sea, off the coast of Govan’s Head [92].

Executive Summary

As the world pivots away from fossil fuels towards a more sustainable energy system, the search for new and improved energy sources has intensified. Among the existing renewable energy options, wind power is a reliable choice, and particularly offshore, where wind velocities are higher and more consistent. Over the past decade, innovations within the sector lead to the pursuit of floating offshore wind farms. While there is a large body of knowledge in relation to the lay-out optimisation of bottom-fixed offshore wind farms, knowledge and research in the lay-out optimisation of floating offshore wind farms are a new territory. As of November 2023, with no papers published on the layout optimisation of floating offshore wind farms, this literature review aims to fill that gap by exploring the existing research landscape.

Therefore, the ambition of this literature review was to explore the existing research landscape and pinpoint the useful knowledge within the context of floating wind farm lay-out optimisation, with an emphasis on the complications of anchor sharing and cable routing. The review delves into the foundational aspects of the industry, examining the need for offshore wind, the rationale behind clustering turbines in farms, and the unique challenges and advantages of floating offshore wind farms. Following this groundwork, conventional, bottom-fixed, lay-out optimisation was researched on both wake avoidance and cable routing. Building on this, the optimisation of floating offshore wind farm layouts was discussed using parallels and differences across a spectrum of research fields. This approach aimed to yield insights into complex problems like anchor sharing and cable routing.

With the extensive knowledge of bottom-fixed wind farm lay-out optimisation as a neighbouring research field, it becomes important which techniques can be transferred towards floating offshore wind, and which cannot. Also, with no research done in the actual field of floating lay-out optimisation, it is important to consider a diverse and broad set of research fields to find optional synergies and other related considerations.

Therefore, the scope of this literature review aimed to identify the, broad, research gap of floating wind farm lay-out optimisation, with a focus on anchor sharing and cable routing. The study did so by first exploring the basis of the industry, namely where the need for offshore wind came from, why wind turbines are clustered in farms and finally why a floating offshore wind farm is advantageous. After this, the conventional bottom fixed wind farm lay-out optimisation is discussed, with both the lay-out problem and the cable routing problem discussed. After this, the floating offshore wind farm lay-out optimisation is discussed by means of finding similar problems and solutions in different research areas.

This literature study finds that floating wind turbines present a solution to exploit deep-water wind resources, though their technology is developing and not yet cost-competitive. This literature study underscores the complexity in designing layouts for floating offshore wind farms (FOWFs), where conventional methods for bottom-fixed wind farms do not suffice, and optimisation strategies need to be altered accordingly. Addressing the primary research question, this study explores the best strategies for reducing anchor and power cable costs in FOWF design, which is critical for economic viability.

Furthermore, this study finds that a discrete and heuristic approach, notably using genetic algorithms, is optimal for Wind Farm Layout Optimisation (WFLO) due to its efficiency and quality of solutions. These strategies, while effective for fixed turbines, require careful application to floating systems due to differing wake behaviours. For Wind Farm Cable Routing (WFCR), a mix of genetic algorithms and Variable Neighbourhood Search (VNS) shows potential, with VNS providing an advantageous flexibility for larger, more complex scenarios. The current literature's scarcity on FOWF optimisation points to a distinct research gap, particularly in the areas of anchor minimisation and cable cost reduction. It recommends a Variable Neighbourhood Search coupled with visibility graphs for WFCR and suggests exploring Mixed-Integer Linear Programming (MILP) and graph theory for anchor optimisation. Conclusively, this literature review identifies Net Present Value (NPV) as a critical success metric, advocating for specialised research in FOWF optimisation techniques to pave the way for more economically and technically viable renewable energy solutions

Contents

List of Figures

Nomenclature

Abbreviations

Abbreviation	Definition
CAPEX	Capital Expenditure
FOWF	Floating Offshore Wind Farm
GA	Genetic Algorithm
LCOE	Levelised Cost of Energy
NPV	Net Present Value
O&M	Operation and Maintenance
OPEX	Operational Expenditure
VNS	Variable Neighbourhood Search
WFLO	Wind Farm Layout Optimisation
WFCR	Wind Farm Cable Routing
WFO	Wind Farm Optimisation

1 Introduction

Ever since the first offshore wind farm was erected nearby Vindeby, Denmark in 1991, with 11 turbines and an annual net output of 9.61 GW-h [88], the quest of increasing the efficiency of wind farms has been present. The cost-efficiency of a wind farm is greatly valued by both the government and the (potential) owner, especially due to the tender-based system used by governments to allocate offshore wind exploitation locations. If a potential owner is able to offer the generated energy for a lower price to the government, the likelihood of the government accepting the bid and the potential owner becoming the actual owner, increases. Next to this quest, the mission to make offshore wind available in greater water depths, and thus expanding past conventional bottom-fixed turbine foundations, posed a second daunting challenge.

The levelised cost of energy (LCOE) is a single number measure for the price an owner is able to deliver energy to the local government. In the industry, this number is often used to indicate the (cost)efficiency of a wind farm, since a more efficient wind farm leads to a lower price of energy. As visible in Figure 1.1, the LCOE of offshore wind has been declining trough out the world and is expected to do so in the coming decades. Some of this is because of improved, and bigger, wind turbines and foundations, and an increase in O&M efficiency. Another influential factor is financing cost [66].

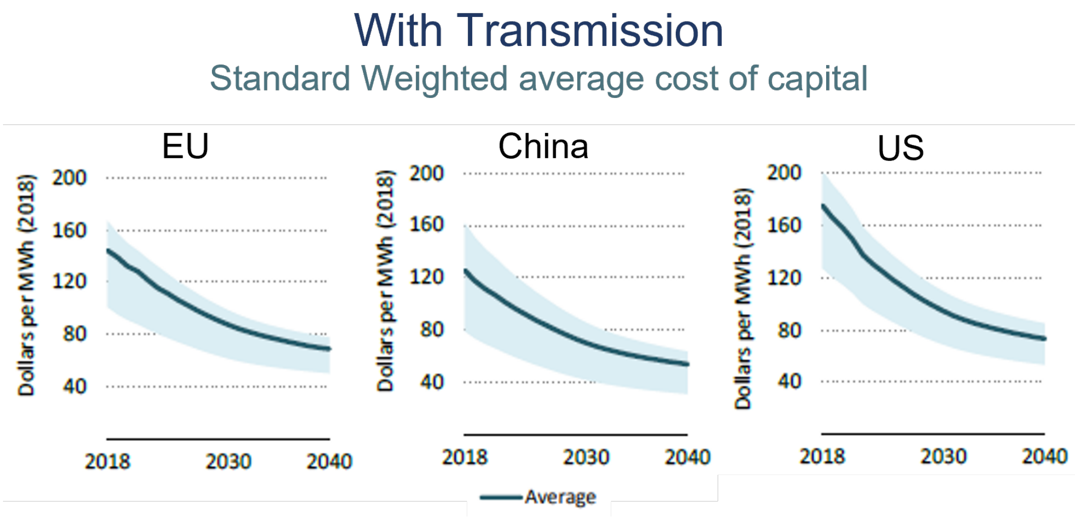


Figure 1.1: LCOE of offshore wind in different parts of the world, altered from [66].

Next to these factors, novel techniques has been developed to optimise the layout of the wind farm and cables even further. By placing the turbines over the available plane more efficiently, energy destroying wakes can be avoided or steered away from downwind turbines. Also, by routing the cables more efficiently through a wind farm, the levelised cost of energy is even further decreased. This leads to innovative configurations of wind farm layouts, as visible in Figure 1.2.

(a) Aerial view of offshore wind farm Gemini, where the turbines are still placed in a grid-like layout, retrieved from [115].

(b) Aerial view of offshore wind farm Kriegers Flak, where optimisation caused an asymmetrical layout, retrieved from [26].

Figure 1.2: Aerial difference between a non-optimised layout and an optimised layout of an offshore wind farm.

Now that sizeable progress is being made on decreasing the LCOE, and with that increasing the efficiency per wind farm, the focus of the industry is shifted towards the second problem introduced. As visible in Figure 1.3, about 51TW of the global offshore wind resource capacity is located in waters too deep for bottom-fixed wind turbines.

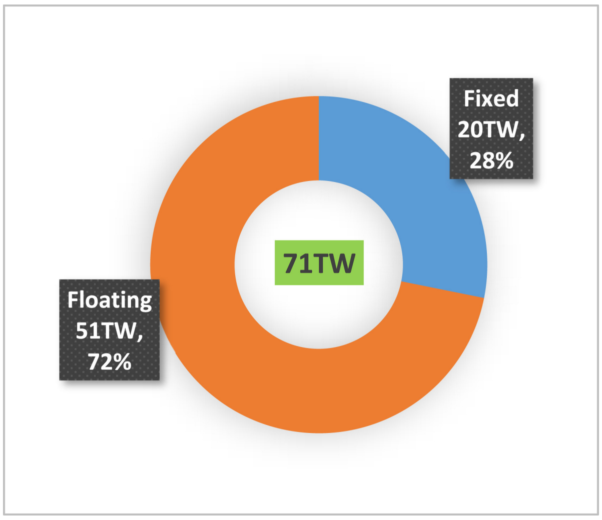


Figure 1.3: Global offshore wind resource capacity, retrieved from [116]

If the water depths are too deep for conventional bottom-fixed turbines, floating turbines can pose a welcome solution. There is a lot of knowledge on floating offshore structures already gathered by the oil and gas industry, and it presents other advantages like a reduced impact on marine life and an increase in consistently high wind speeds.

However, when designing a floating wind farm, other problems rise to the surface in order to reduce the LCOE. Firstly, the expensive anchors pose a serious cost challenges. Secondly, because of safety reasons, it is impossible to route a cable over or under another line. This means that it is also not possible for the power cable to cross the lines connecting the anchor and turbine, called mooring lines, in the entire vertical plane of the cables. These two problems ask for a different approach compared to previous problems or problems seen in the location optimisation of bottom-fixed wind farms, revealing the true goal of this thesis: Exploring ways to optimise the layout design of a floating offshore wind farm, to further decrease the LCOE.

1.1. Research Questions and Literature Study goal

The research question of this Master Thesis research is the following:

RQ. *What is the best strategy for minimising the amount of anchors while also minimising the power* *cable costs when designing the layout of a floating offshore wind farm?*

To answer this research question, the following sub-questions need to be answered first:

SQ1. *Which similarities can be found and adopted from literature?*
SQ2. *What is the best metric or criterion for success of a strategy?*
SQ3. *What is the best strategy to minimise the amount of anchors in a floating offshore wind farm?*
SQ4. *What is the best strategy to minimise power cable costs in a floating offshore wind farm?*
SQ5. *What is the best way to combine the goal of minimising the amount of anchors and minimising the cable costs?*
SQ6. *Which ambient factors influence different strategies negatively, and to what extent?*
SQ7. *Is the energy yield of the wind farm negatively influenced by the strategy, compared to a bottom-fixed layout and if so, by how much?*

This literature review aims to fully answer SQ1 and SQ2, and provide a sufficient base for the other questions. The main thesis aims to answer the other sub-questions fully by constructing an optimisation model and comparing different results. Moreover, this literature study seeks to establish sufficient background knowledge to approach the rest of the thesis adequately, and to start building a model with plentiful foundation.

1.2. Outline

This literature study is structured as follows: chapter 2 establishes the foundational knowledge about the offshore wind industry, with a focus on the emerging technology of floating offshore wind. In chapter 3, the existing expertise on layout optimisation of bottom-fixed offshore wind farms is examined to identify potential synergies for application in floating offshore wind. chapter 4 delves into the current state of optimisation strategies for floating offshore wind farm layouts, exploring potential intersections with various other research domains. The study culminates in chapter 5, where the findings are synthesised into a cohesive conclusion.

2
Offshore Wind

To lay the groundwork for this literature review, it is essential to examine the origins of the need for offshore wind and the accompanying key requirements. The reasoning behind offshore wind is explored in the first section of this chapter. Subsequently, the focus shifts to the development, the design, and the essential characteristics of offshore wind farms, to provide a more in depth look into their place in the industry. Finally, the chapter compares and contrasts floating offshore wind with bottom-fixed offshore wind, leading to a discussion of the advantages and challenges inherent in floating offshore wind technology.

2.1. Need for Offshore Wind

In this section, the need for offshore wind is discussed. This is done by setting the stage with the global reliance on fossil fuels. Then renewable energy sources are introduced. After that, the solution that is offshore wind energy will be introduced.

2.1.1. Fossil Fuels

Traditionally, fossil fuels are the main energy source worldwide. European countries still depend heavily on fossil fuels. In 2016, for most European countries, around 60% of the energy consumption came from fossil fuels. When looking to Europe, data shows that in 2016, 10 countries' energy consumption was for 80% or more supplied from fossil fuels [83, p.9]. Outside Europe, other countries like South-Korea, Russia and China reach almost 90% of energy consumption from fossil fuels in 2015 [23, Tab.1]. And as visible in Figure 2.1, there is no substantial decline in the trend visible yet.

One of the main concerns with the use of fossil fuels is its inherent exhaustibility. There are only so many kilograms of fossil fuel in the world, and although there are arguments that state that the need for fossil fuels will drive innovation towards new ways of extracting them, they will eventually run out. For oil, gas and coal this is calculated respectively at 21, 23 and 93 years. This means that after 2042 coal will be the only fossil fuel remaining [103]. Although these numbers are disputed since they have been written down, it gives an indication that fossil fuels might not even be able to live through the current generation. This decrease in supply, only increases the price of energy, putting a hold on economic growth [75].

Another big disadvantage of fossil fuels is its connection to geopolitical tension. The prices are volatile, and can thus be used to assert geopolitical pressure from country to country. On the flip side, this also means that countries can never operate independently, increasing collaboration between nations.

A third disadvantage of fossil fuels is its danger for health and local environment quality. Not only air is heavily polluted by the use of fossil fuels, but also water and land. In many cases, by releasing fossil fuels without proper disposal. But land is also eroded away by the extraction of fossil fuels [8, p.5].

Last, but certainly not least, fossil fuels are a main driver of increasing greenhouse gasses [112]. This in turn increase the worldwide temperature, which leads to climate change. In 2022 global CO_2

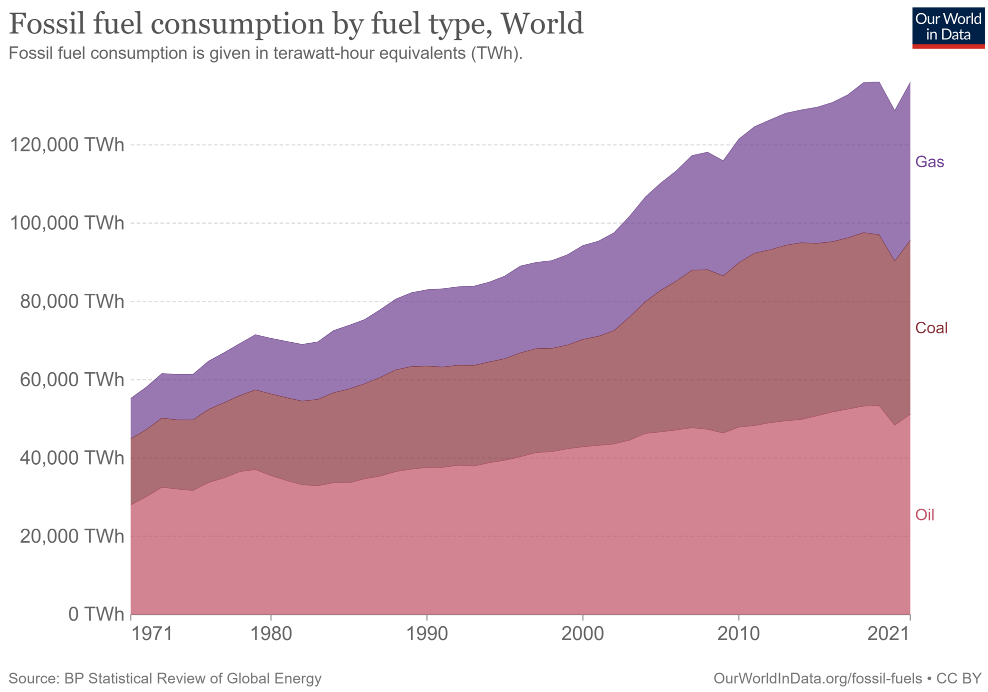


Figure 2.1: Global fossil fuel consumption by fuel type [102].

emissions from coal increased by 1.6%, and global CO_2 emissions from oil increased by 2.5%. However, CO_2 emissions from natural gas fell by 1.6%, due to restrictions by the European Union regarding the invasion of Ukraine by Russia [68, p.3].

Concluding, fossil fuel is a convenient energy carrier, with widespread infrastructure in place. However, its negative sides are undeniable and leads to a desire for a sustainable alternative. This is why, in 2020, the European Union have set clear goals for 2030 and on wards: Reduce greenhouse gas with 55% by 2030 with respect to 1990 [38, p.2]. Furthermore, the European Union aims to achieve net-zero CO_2 emissions by 2050 [33, p.5]. Other parts of the world have also committed to the goal of reducing climate change through the 2015 Paris Agreement. However, this agreement focuses on reducing global temperature increase rather than setting specific $CO2$ emission reduction goals like those set in Europe.

2.1.2. Renewable Energy

To avert these negatives, the focus of future energy has been shifted more and more towards renewable energy sources. A variety of different sources have been explored, and every region of the world prefers another as the main sustainable energy source.

Globally, the most popular options are solar energy, wind energy and hydropower [102]. An overview of the different renewable energy sources and their growth throughout the years is depicted in Figure 2.2.

In 2020 the capacity of sustainable energy grew at its fastest rate in 20 years, with solar and wind energy accounting for the bulk of it. Around 50% of the new sustainable energy capacity is solar energy and around 40% is wind energy [69]. On the other hand, hydropower has been around and popular for a longer time [113]. With the easy ability to store energy, namely by blocking the water flow, hydropower has a major advantage over the other two. However, hydropower also shows significant environmental impact. For instance, the influence on river meandering, wildlife mitigation and wildlife habitat loss [114].

Other options for sustainable energy are geothermal, biomass and ocean energy. These options, however, show less resource availability and are not as cost competitive as solar and wind [3]. This is why it is expected that wind and solar will provide the greater part of our energy needs in the future, although it might differ per region of the world [110]. It is also suggested by Ang et al. [3] that a hybrid

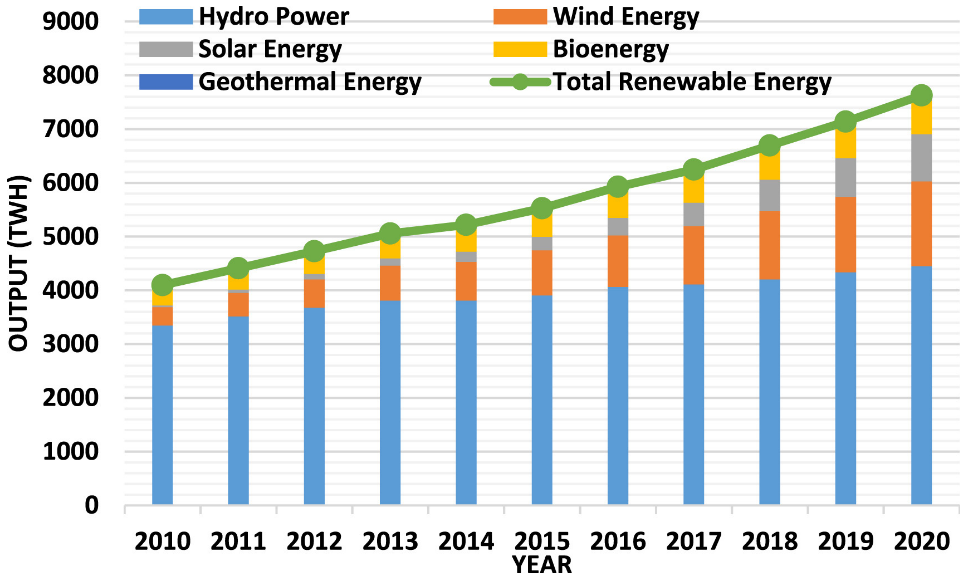


Figure 2.2: Total share of global renewable energy usage, split by type of source [3].

combination of renewable energy systems is able to overcome the shortcomings of a single source of renewable energy.

2.1.3. Offshore Wind Energy

The cost of wind energy is predicted to drop between 37% and 49% by 2050, however future costs predictions also entail a certain level of uncertainty [119]. The amount of wind energy captured by wind farms will most likely increase, the quantity of this increase depends mainly on policy [110].

There are two primary categories of wind energy: onshore and offshore. Onshore wind turbines are located on land, while offshore wind turbines are situated off the shore. Onshore wind turbines have lower operation and maintenance costs, but offshore wind turbines can produce more power due to their larger size and higher wind speeds. Additionally, offshore wind turbines have less impact on the environment, with lower levels of noise and visual disturbance.

Furthermore, onshore wind deals with a more limited area suitable for development in comparison with offshore wind. With every developed onshore wind farm, the capacity factor (a measure for the efficiency of a wind farm or single turbine [14]) will decrease and the resistance of population groups in the area will increase [61, p.1]. This will result in a further decrease in the amount of potential areas suitable for onshore development.

In [61] a comparison between offshore and onshore wind is made with the use of ”acceptance costs”. Three different methods are used for the calculation of acceptance costs. One is based on the compensation and property purchase cost, the other on the property value loss induced by the wind turbines, and the last method is based on the willingness to pay [15]. In this study, Hevia-Koch found that including the acceptance costs, onshore wind farms are still more cost advantageous in comparison with offshore wind. However, the study does mention that the Levelised Cost of Energy (LCOE) of offshore wind show a fast decreasing trend, particularly compared to onshore wind.

Another study, by Enevoldsen and Valentine, concludes that offshore wind farms produce higher energy levels than onshore wind farms [36]. However, Enevoldsen state that this is not the consequence of a higher capacity factor, but because of the scale difference between both types of sites. Because of the higher costs accompanied by offshore projects, developers increase their turbine size, thus yielding more energy. An important note is that it is also easier to obtain permits for bigger wind turbines offshore than onshore, because of the increased social acceptance offshore [85]. This is a consequence of the correlation between turbine size, more specifically blade size, and the acoustics emissions by the blade [12].

Other sources say that it is clear that offshore wind farms see higher wind speeds and thus produce more energy [105].

Concluding, offshore wind shows great potential to grow into our future energy production system as a permanent member. It will most likely not be the only member, but the hybrid of renewable energy resources fulfilling our future energy needs will probably entail offshore wind. Furthermore, the current size of offshore wind is expected to grow, and offshore wind is expected to become more cost advantageous in regard to onshore wind [30]. All in all, enough reason to further explore the possibilities and limitations of offshore wind as an energy source.

2.2. Offshore Wind Farms

For offshore wind to be economically viable, it is wise to exploit the economies of size. By placing multiple turbines at one location, they can share (electrical) infrastructure and maintenance. Also, the cost of construction will drop when multiple wind turbines are constructed at once. Furthermore, it is more efficient to investigate different environmental aspects of the designated area. With all these wind turbines in one location, a literal ”wind farm” arises.

In the next section, typical offshore wind farms are explored and explained. This is done by first giving an explanation on the general blueprint. Consequently, the wake is explained. Hereafter, the environmental analysis, which includes soil investigation, is explained. Finally, the design process of an offshore wind farm is explained.

2.2.1. General Blueprint

An offshore wind farm generally consist of the following parts. Multiple turbines, each with its own foundation, transferring kinetic wind energy into electrical energy. When this kinetic energy is captured, the electrical energy is collected in substations and then transferred trough cables to the shore.

In the following subsection, an overview is offered of the different components that are universal throughout offshore wind farm design.

Turbine

An offshore wind turbine broadly consists of five components, as depicted in Figure 2.3.

Firstly, the rotor. This part connects the blades and spins the drive shaft, which is hosted in the nacelle. The nacelle contains a drive shaft and a generator to transfer the kinetic energy of the rotor turning into electrical energy. The rotor is being turned by the blades attached to it. Most offshore wind turbines consists of three blades at alternate locations. More blades would mean less noise, but also a more expensive rotor. Fewer (two) blades would mean more noise, but a cheaper rotor. Historically, the noise was of great concern when the development of wind farms commenced on shore. This is why the three bladed rotor is preferred. When offshore wind was developed, initially, the three bladed onshore rotor was adopted. Lately, some voices have started to advocate a two bladed rotor, stating that noise is of less influence offshore. This would reduce the torque and costs of the rotor.

Another development in offshore wind is the increase in diameter of the blades and thus increasing the size of the tower [30].

As mentioned, the nacelle hosts the drive shaft, the gearbox, the yaw gear, brake and control systems for the aforementioned mechanical systems. Furthermore, the nacelle contains some weather instruments. And with the increasing size of the blades and rotors, the nacelle grows with it. They weigh between 150 - 300 tonnes and even host helicopter platforms and built-in service cranes [59].

As wind turbines have grown taller in recent years, their towers have become increasingly important in raising the nacelle and rotor to greater heights. The benefits of height are numerous, as turbulence decreases with increasing elevation. This means that wind turbines can generate more electricity with greater efficiency and reliability when placed at higher altitudes. So, as the tower grows taller, so too does the potential for increased energy production from wind power.

There are different types of foundations used to secure the wind turbine in its desired location. These are further explained below.

Foundation

An overview of the foundation types used in offshore wind is depicted in Figure 2.4, except for a floating foundation. Different foundations have different advantages and disadvantages. Also, the popularity of different foundations differs per region of the globe, mainly because of the difference in depth and soil conditions of different seabeds.

More on floating foundations in section 2.3.

Electrical Infrastructure

The goal of the electrical infrastructure of the offshore wind farm is to transfer the electrical energy captured by the wind turbines towards the shore and into the national grid. For that goal to be accomplished, cables and substations are needed to transfer the electricity effectively and efficiently [52].

Concerning substations, offshore wind farms include an offshore and onshore substation if the project contains enough turbines and is located far enough from shore. Most of the future projects

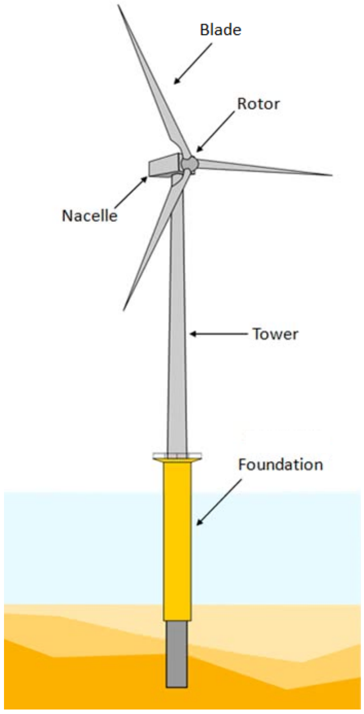


Figure 2.3: General components of an offshore wind turbine. Altered from [118].

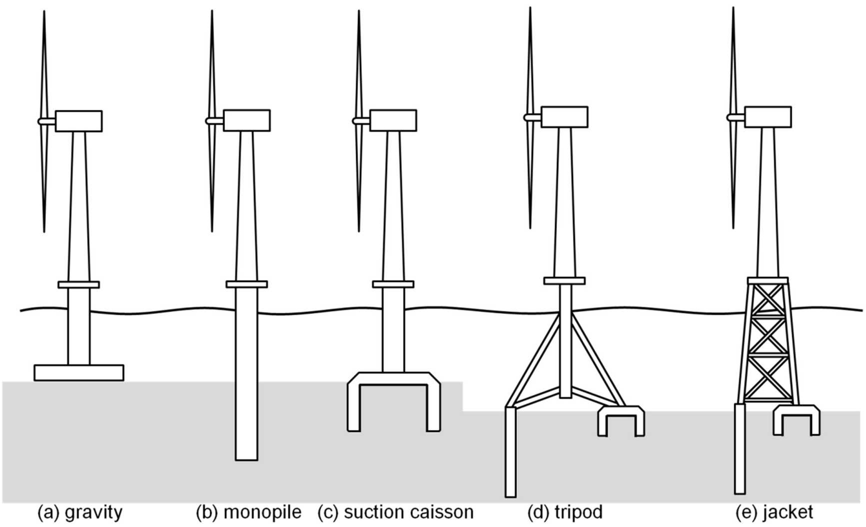


Figure 2.4: Types of fixed-bottom foundations used in offshore wind farms [93].

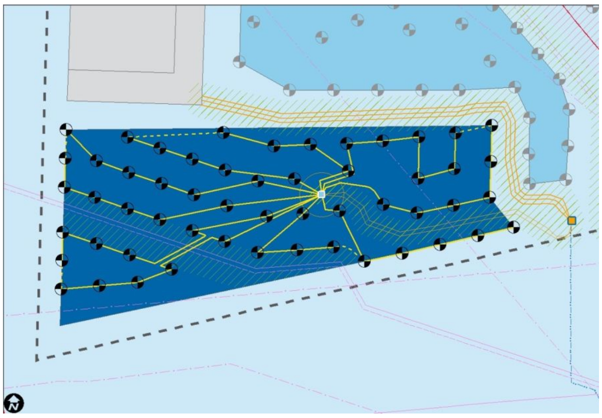


Figure 2.5: Configuration of the inter array cable layout of Nordsee One [67].

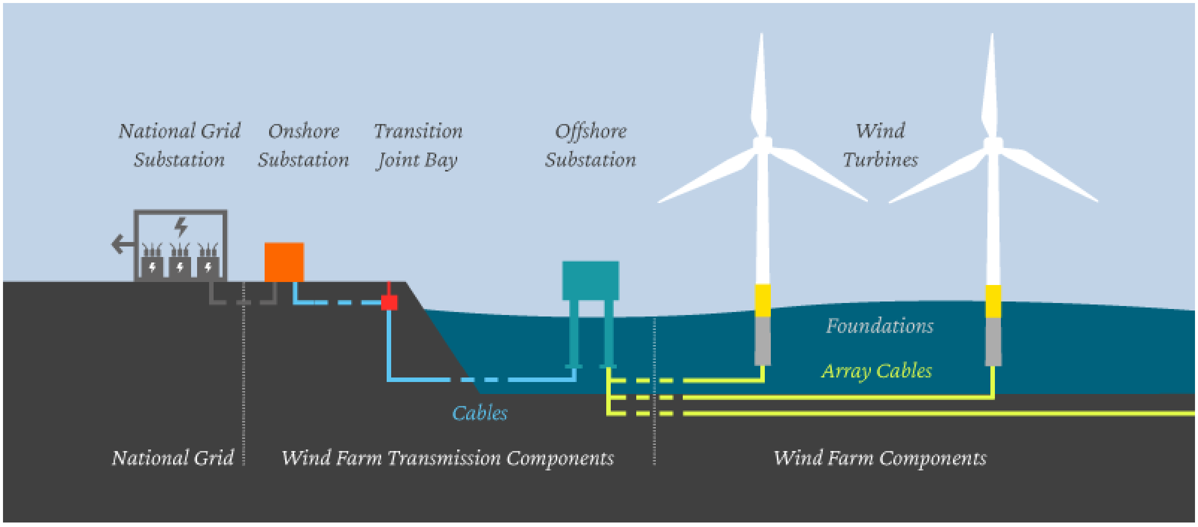


Figure 2.6: Overview of the electrical infrastructure of an offshore wind farm [39].

will need one or more offshore substations, as the current big projects already employ multiple substations. The offshore substation is responsible for collecting the electricity from the different inter array cables and increasing the voltage. An offshore substation can contain one or more transformers, which increase the voltage. The increase in voltage decreases the losses in electrical transferring, because the power is also decreased. Another function of the modern offshore substation is to provide a terminal to the offshore wind farm, sometimes even equipped with a helicopter deck. At an onshore substation, the voltage is further increased, and the electricity is prepared to be offered to the network operator. This is done onshore to reduce operating and maintenance costs.

Regarding cables, three categories of cables are needed for an offshore wind farm. Firstly, the aforementioned inter array cables are needed for connecting the different wind turbines to the substation. As an example, the inter array cable layout from Nordsee One, a wind farm in front of the German coast, is depicted in Figure 2.5. The diameter, and thus technical specifications, of an inter array cable can differ within one wind farm, depending on how many turbines it connects. The inter array cables are buried in the seabed, and emerge at the turbines and substations. Furthermore, one export cable is needed per transformer to transfer the electricity from the offshore substation towards the onshore substation. These cables are then buried and laid to shore. A secondary note is that these export cables contains electrical connection both ways, to also deliver electricity to the wind farm if start up electricity is needed.

An overview of the electrical infrastructure of an offshore wind farm is given in Figure 2.6.

Figure 2.7: Low-hanging fog makes the wake visible in wind farm Horns Rev 1. Image copyright Vattenfall 2022

2.2.2. Wake

One of the major disadvantage of an offshore wind farm in comparison to an individual offshore wind turbine are the wake effects induced by one wind turbine on the other. A first turbine extracts kinetic energy from the wind and casts a ”shadow” of reduced wind speeds and increased turbulence on the turbines behind it. Low-hanging fog makes this phenomenon visible, as is shown in Figure 2.7.

The wake effects of a wind turbine are important for a few reasons. Firstly, the wake effects extend over 50 kilometres with stable atmospheric conditions, and can thus easily span the entire wind farm [81]. There is even evidence of wind farms influencing other wind farms with its wake [91][95]. Secondly, when looking at a single downwind turbine, wake effects heavily influence the total productivity, reducing its power output by 20 to 46% [1]. Thirdly, the wake effects increase downwind turbulence, which in turn increases the fatigue load on the turbines [73]. An increase in fatigue load means that the expensive wind turbines will have a shorter lifespan, but also it means a disproportionately distributed repair need over the wind farm. This will lead to an increased cost in operations and maintenance.

All in all, it can be concluded that these wake effects are of great importance. For the development of accurate plans to minimise the consequence of the wake effects, a lot of energy is put into correctly defining the wake effects. However, because of the irregularity of turbulent flows and their inherent unsteadiness, wind turbine wake effects are hard to describe deterministically. More often, they are described statistically with the use of computational fluid dynamic models. In practice, multiple models are used to correctly forecast the wake effects, depending on the goal of the simulation. Regarding energy output, the most popular models, Jensen wake model, two-dimensional (2D) Jensen wake model and Jensen-Gaussian wake model, do not show any significantly different results [107].

Multiple tactics have been developed to reduce the consequences of the wake effects within a wind farm. First, by placing the wind turbines as far away from each other as possible. Second, active wake steering shows a lot of promise. This is done by tilting the blades and yaw of a turbine. However, in practice, it is hard to measure the true effects of active wake steering. One study have found that wake steering can result in a 6.6% decrease of wake losses [51].

2.2.3. Environmental Analysis

A few aspects of the surrounding environment where the wind farm is located are particularly noteworthy.

Firstly, a good understanding of the wind characteristics of the wind farm site needs to be acquired. Often times, this information is illustrated using a wind rose. An example of a wind rose is given in Figure 2.8.

A wind rose is created by averaging the wind speed and direction over a short time interval for a longer period of time. The results are plotted on a circle. The direction of the bar indicates from which direction the wind blows, the colour indicates the wind speed, and the distance from the centre of the circle shows the probability of the combination of this wind speed and direction occurring. Most of the time, a wind rose is height averaged over the radius of the turbines' blades. For the optimisation of a wind farm, the most common combination of wind speed and direction is sufficient.

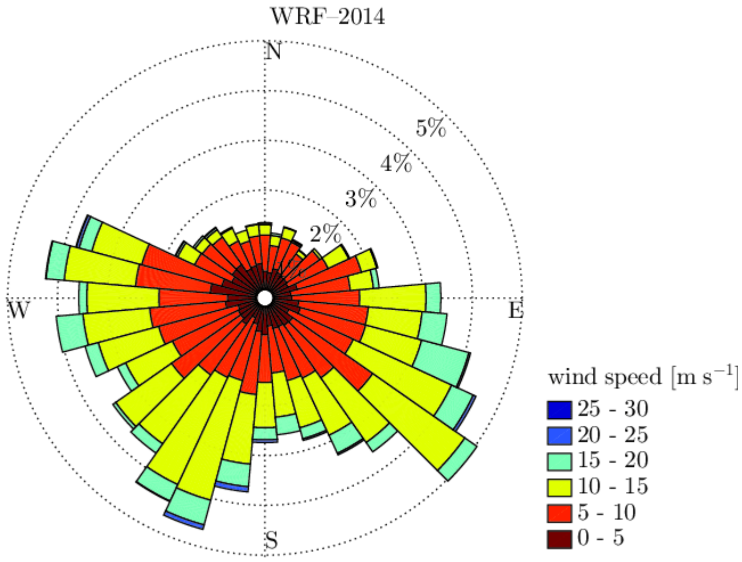


Figure 2.8: Height averaged wind rose of Anholt windfarm for the year 2014, retrieved from [77].

Secondly, the soil conditions and possible presence of obstacle forming boulders is also noteworthy. The soil conditions can point to more and less favourable positions for the wind turbine, where obstacles, like boulders, can identify places where foundation and cables cannot be placed.

Lastly, ecological factors are becoming more and more present in decision-making of the development of an offshore wind farm. These factors focus around the preservation of the current marine ecosystem [53].

2.2.4. Development Process of an Offshore Wind Farm

The development of an offshore wind farm consist of many different steps. Foremost, it is good to know that the area is tendered by the government. Different contenders assess the area and propose a business plan to exploit the area with a wind energy farm. The government then selects the most competitive bid. The levelised cost of energy plays a big part in this, but more recently also less quantitative factors became important, such as the impact on marine life, and if the wind farm fits inside a circular economy.

When the bid is announced, and an offshore wind farm developer starts developing the wind farm, the steps as depicted in Figure 2.9 need to be conducted. First, the site-specific requirements are collected. After that, the technologies available by different suppliers are reviewed. After that, the first few optimisations are made, centring around a turbine type selection and cable type selection. With this information, the supplier can be selected, and the final design can be created. The offshore wind farm developer now hopes that the bid is competitive enough and will be picked by the government.

Optimisation Metrics

A variety of metrics can be used to determine the efficacy of a wind energy project [32]. The aforementioned Levelised Cost of Energy (LCOE) compares the Capital Expenditure (CAPEX) and the Operational Expenditure (OPEX) with the Annual Energy Production (AEP) as described in Equation 2.1. The OPEX and AEP are discounted over a lifetime N (in years) using *r*. This is the interest rate, in percentage.

$$\text{LCOE} = \frac{\text{CAPEX} + \sum_{t=1}^{N} \frac{\text{OPEX}_t}{(1+r)^t}}{\sum_{t=1}^{N} \frac{\text{AEP}_t}{(1+r)^t}} \tag{2.1}$$

The LCOE is useful to compare different technologies with each other, such as floating offshore wind against bottom-fixed offshore wind. To compare different solutions from one technology with each other,

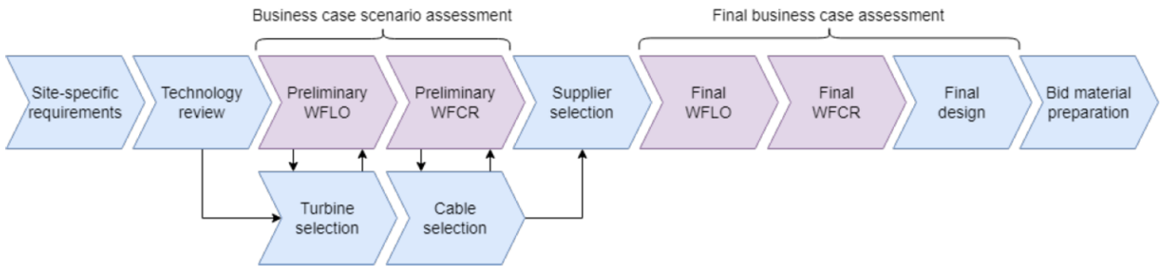


Figure 2.9: Design process of an optimized offshore wind farm, after the bid has been secured. Retrieved from [17].

the Net Present Value (NPV) is more often used [17]. The formula for the NPV is given in Equation 2.2. In this equation, all variables are taken on a per-year basis.

$$\text{NPV} = \sum_{t=1}^{N} \frac{\text{Revenues}_t - \text{Costs}_t}{(1+r)^t} \tag{2.2}$$

Because in all these formulas the revenues are taken into account, this means that great uncertainty is introduced. Weather and turbine availability greatly influence the NPV and the LCOE. This means that it is hard to compare different solutions without having a thorough view inside the variance of the revenue.

Also, when sharing anchors or minimising cable cost, no difference in revenue will be obtained. That is why it is decided that the overall CAPEX cost of the anchoring and cabling is the most objective value to compare different solutions for this master thesis. Only if also the turbine layout optimisation will be taken into account, the NPV will be used. When the turbine layout will also be optimised, the difference in revenue will also be present, and then the NPV will be a better metric.

2.3. Floating Offshore Wind Farms

In this section, a general introduction to floating offshore wind farms (FOWFs) is provided. First, the similarities and differences between floating offshore wind farms and their bottom-fixed counterpart will be highlighted. Second, the advantages and challenges of a floating offshore wind farm will be discussed.

2.3.1. Similarities and Differences

Floating offshore wind farms show similarities with bottom-fixed wind farms. FOWFs are able to use the same turbines as their bottom-fixed equivalent, which accounts for a large part of the operations and maintenance and costs of a wind farm [106]. Furthermore, FOWFs are also connected to a substation and

FOWFs also differ to bottom-fixed on two points. First, the most obvious, floating wind farms have a different foundation in comparison with bottom-fixed wind farms. The foundation consist of a floating platform and a system of mooring lines and anchors. Second, because of the floating turbine, a different, more dynamic, connection to the electricity grid is needed [108]. This is why the cable connections of FOWFs also differ.

Foundation

Where in a bottom-fixed turbine the foundation is used to keep the turbine in the same position, for floating turbines the function of keeping the turbine in the same position and structurally stable is fulfilled by two systems. Firstly, the platform on which the turbine is placed, which uses buoyancy in some form to stay, partly, on top of the water and stable. And secondly, the mooring lines and anchors to keep the floating turbine in place.

There are different types of platforms available for floating wind turbines, as depicted in Figure 2.10. To further elaborate on the differences and advantages between the different platforms reaches outside the scope of this literature review.

As noted before, the mooring lines and anchors keep the floating turbine in place, commonly referred to as anchor systems. There are four main systems in the industry and a few innovative systems

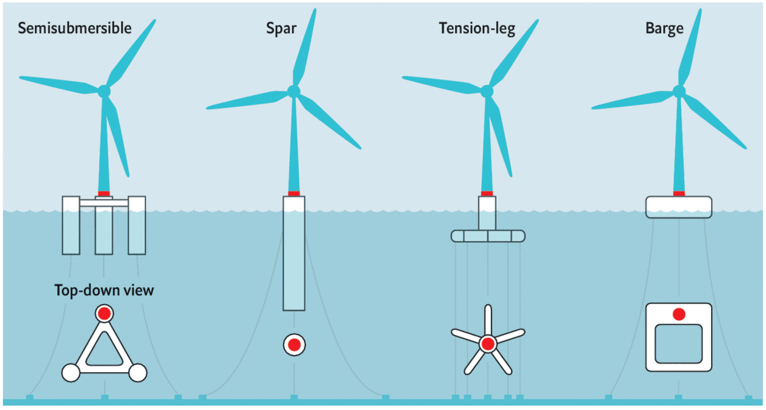


Figure 2.10: Floating wind farm platform categories, retrieved from [86]

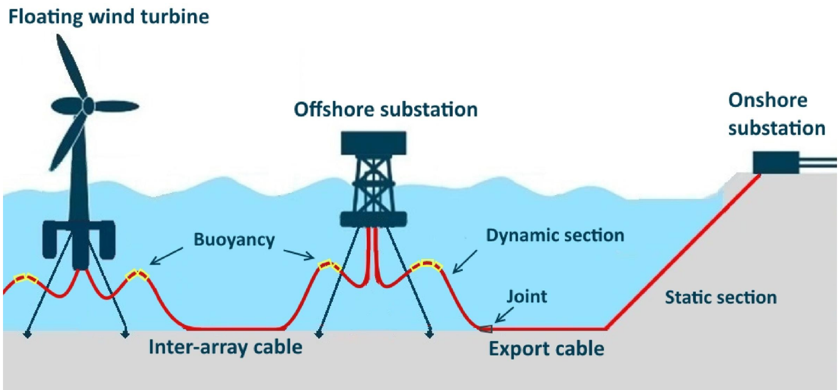


Figure 2.11: Overview of the electrical system of a floating wind turbine, retrieved from [78].

that fall out of the scope of this research. First, there is the gravity-base anchor. This system utilises heavy dead weight to ensure capacity against vertical and horizontal forces. Second, a drag-embedded anchor, which is dropped to the seabed and dragged across it to establish a deep embedment into the seabed. Thirdly, there are driven pile anchors, which uses an impact or vibratory hammer to establish a permanent connection to the seabed. Finally, suction anchors use a suction to create a firm connection to the seabed. The difference between installation of these anchor systems is that drag-embedded anchors need more space, to be dragged into place. However, the differences between these anchor systems are beyond the scope of this study and therefore the assumption is made that the anchors are already in place.

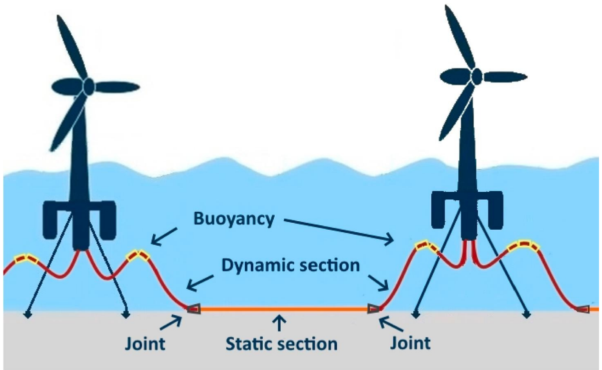
Electrical Infrastructure

The electrical infrastructure of a floating offshore wind farm is depicted in Figure 2.11. The electrical system entails inter-array cables, an offshore substation an export cable and an onshore substation, with joints and dynamic sections connecting the different parts.

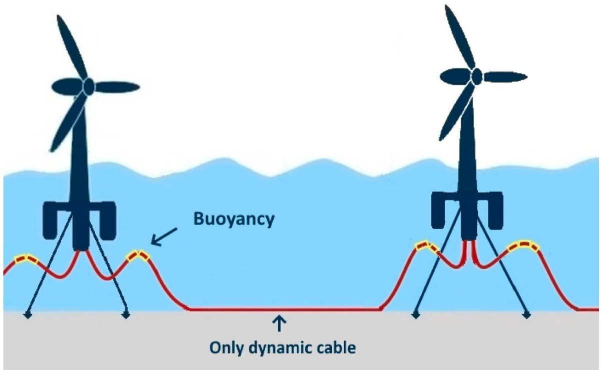
In order to withstand the waves, currents, seabed interactions and motions of the floater, the dynamic section requires flexibility and mechanical strength.

The export cable is deemed out of the scope of this study, because little gain can be obtained from optimising this. The offshore substation is also placed on a floating structure and needs to be anchored, but does not differ any further from a conventional offshore wind farm substation, which is explained in Figure 2.2.1.

The inter-array cables use so-called risers, originating from the oil and gas industry, and utilises buoyancy to reduce the load on the cable. A number of different risers exist: lazy wave, steep wave, lazy S and others [22]. The lazy wave variant has been chosen in the currently operating FOWFs Hywind [126] and Fukushima [122], and is also the variant depicted in Figure 2.11. Another decision can be made when designing the inter-array cable layout of an offshore wind farm. It is possible to let the



(a) Dynamic with static cable configuration



(b) Dynamic cable only configuration

Figure 2.12: Overview of different inter-array power cable configurations, retrieved from [78].

cables have a static section and a dynamic section, however, expensive submarine joints are needed for this. Another possibility is to let the cable entirely be made of a dynamic section. Per instance, it might differ what is more advantageous. An overview of the two options is depicted in Figure 2.12.

Wake

The wake propagation in a floating offshore wind farm differs significantly from a bottom-fixed offshore wind farm. The near wake will be increased in width and turbulence intensity by the periodic change of pitch angle. Also, the aerodynamic coefficient can fluctuate as highs as 32.8% by an increased pitching motion. Furthermore, the influence of amplitude on wake velocity is bigger than the influence of frequency [117]. All this means that a new wake model for floating offshore wind is necessary, and a bottom-fixed wake model will probably not be sufficient in accuracy. Increased attention towards the wake model used is thus necessary.

2.3.2. Advantages and Challenges

The advantages of floating offshore wind are threefold, with symbioses between the three categories. Firstly, floating offshore wind has the ability to utilise more space and use it more efficiently. Secondly, floating offshore wind shows the potential of cost reduction. Third, and lastly, floating offshore wind has a lesser impact on the environment. Also, some challenges of floating offshore wind are discussed. An overview of the benefits of floating offshore wind farms is given in Figure 2.13.

Space

The increase of infrastructure offshore leads to an increasing demand for wind-rich areas, like the North Sea, to build offshore wind. Also, as said previously in subsection 2.2.2 a wind farm can lead to wake effects for several kilometres downwind, further reducing the amount of wind-rich areas offshore.

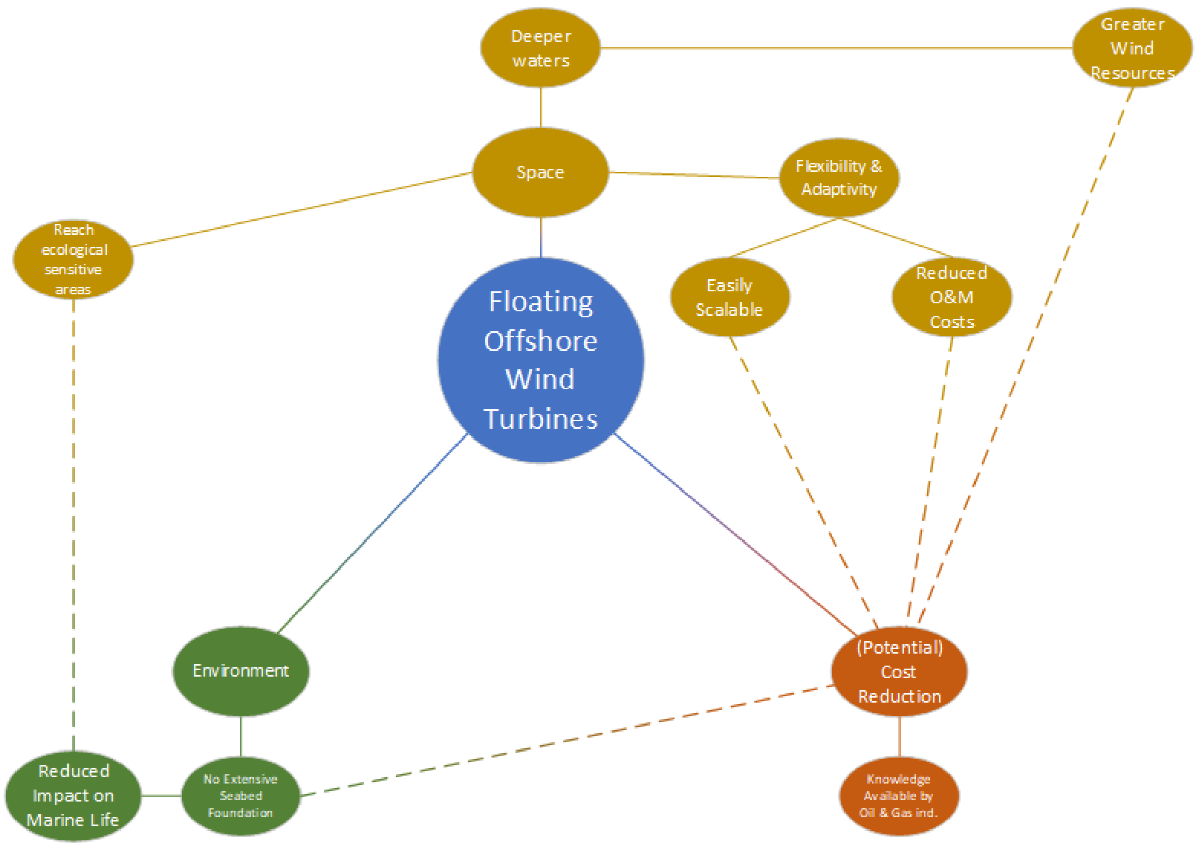


Figure 2.13: Overview of the benefits of floating offshore wind, where synergies are displayed by dashed lines.

By using floating offshore wind turbines, deeper waters can be exploited for the purpose of wind energy generation, reaching more wind-rich areas. Especially, because the deeper waters tend to have greater wind resources, further increasing the capacity factor and showing potential for decreasing the LCOE, symbiosing with the cost advantage. It is expected that the viable area for wind energy increases by a factor of five by introducing floating wind [90].

Another advantage of offshore wind turbines, regarding space, is the flexibility and adaptivity a non-permanent foundation introduces. This flexibility results in a more easily scalable and adaptable wind farm, should factors change. Also, this flexibility shows the potential of reducing O&M costs because wind turbines can be towed away and repaired onshore, also showing symbiosis with the costs advantage.

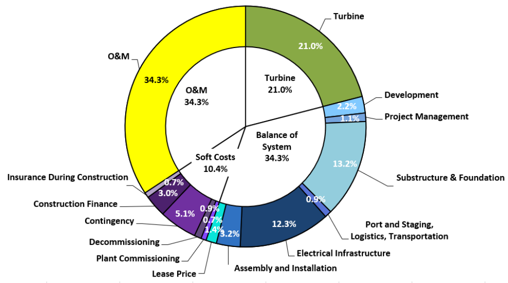
Costs

Despite the fact that the cost advantage is not fully realised yet, experts believe that floating offshore wind will become cheaper than the fixed-bottom alternative, if commercialisation will prove to be successful [10]. As visible in Figure 2.14 a relatively bigger part is spent on "Balance of system", for floating offshore wind turbines. This means that floating offshore wind requires other cost and labour parameters than a bottom-fixed offshore wind.

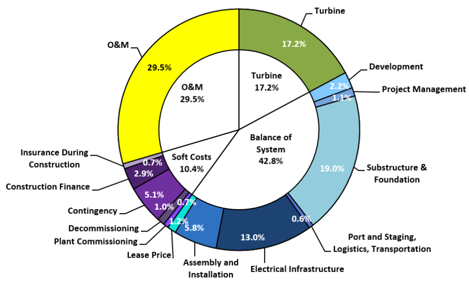
A promising fact is that a lot of knowledge for the technology behind semi-submersible structure originates from the oil and gas industry, meaning that there is less initial research cost in developing the first generations.

Environment

Lastly, floating offshore wind turbines are more environmentally friendly. Reducing cost by not having to install a bottom-fixed turbine in the seabed also reduces the impact on marine life. Extensive foundation installation operations are no longer needed. However, some people also point to the fact that current bottom-fixed foundations provide shelter for marine life.



(a) The cost breakdown of a bottom fixed offshore wind turbine.



(b) The cost breakdown of a floating offshore wind turbine.

Figure 2.14: Cost breakdown of different types of offshore wind turbines, retrieved from [106].

Because it is thought that the impact on marine life is lesser, even more areas become viable for offshore wind, as the concern for marine impact is reduced.

Challenges

Some challenges arise within floating offshore wind. These challenges can be split into two sections. First, there are the challenges that are linked to the stage floating offshore wind is in. Since the technology is quite novel, some challenges arise, but they are expected to be solved in the near future. Second, there are challenges that are inherent to the technology and not related to technological development.

First, the 'grow pains' of floating offshore wind. Because floating wind is expected to be placed in deeper waters, O&M vessels that are able to reach deeper waters need to be developed, and port infrastructure needs to be altered to that. Also, dynamic power cables need to be developed. This can be especially challenging since the static high-voltage power cables of fixed-bottom offshore wind farms were troublesome to develop [80]. Next to that, because it is new technology, not only the initial investments are higher, also it is more likely to fail in early projects.

For the second section, the more permanent problems, there are two main issues. Firstly, because the anchor and mooring line can extend quite far next to the turbine, more space is needed to place the same amount of wind turbines. So floating offshore wind turbines have more space available, but use the space less efficiently. And secondly, because of their far distance to shore, floating offshore wind farms require long-distance solutions to carry the produced electricity towards shore, resulting in expensive power cables. A hydrogen production plant could be a potential solution for this problem. This is because a gas, like hydrogen, can be transported trough, cost-effective steel tubes, in contrast to the expensive power cables required for the transportation of electricity.

3

Bottom-fixed Offshore Wind Farm Optimisation

When designing offshore wind farms, there are traditionally two challenges that are tried to be solved from optimisation techniques.

Firstly, the placement of the wind turbines within the wind farm. Often times, the goal is to maximise energy yield and minimise wake losses. This is called Wind Farm Layout Optimisation or WFLO.

Secondly, the routing of the cables connecting the turbines with substations is also often optimised. This is known as Wind Farm Cable Routing or WFCR.

The profit of wind farm optimisation (or WFO) can be substantial. In an industry where the LCOE not only determines the success of a project, but also if the project ever sees daylight, every dollar saved can be of great impact. In this literature review, a focus is laid on the optimisation of the design of a floating wind farm.

Because of the NP-hardness of these problems, they can be very computationally expensive to solve. Often times this leads to researchers searching for ways to decrease the computational cost by compromising on solution quality. The goal of these techniques is to compromise the quality of the solution as little as possible, while decreasing the computational cost as much as possible.

WFO tries to maximise the energy yield per farm, while minimising CAPEX. As described in [21], there are multiple ways of approaching WFO. An overview of the current techniques will be given in this chapter.

3.1. Wind Farm Layout Optimisation Problem

In this section, the WFLO problem will first be introduced. Thereafter, an overview of the current techniques of solving this problem will be offered, which are broadly split into continuous approached techniques (called Unrestricted WFLOP in literature [21]) and discrete approached techniques.

3.1.1. Problem Introduction

The WFLO problem aims to determine optimal locations for a set of wind turbines within a pre-defined wind farm site. The objective is often to reduce the LCOE or net present value and with that minimise wake interference between turbines. This is done by taking external factors into account such as water depth (influencing the tower height), seabed conditions (influencing foundation cost) and wind roses (influencing wake propagation). Ozturk and Norman [6] denoted the similarity with the *undesirable facility location problem*, since the presence of a facility adversely affects the nearby facilities.

Number of Turbines

As the government releases tenders for offshore wind farms, they also provide the boundaries to the site and GIS information (wind conditions, sea bed conditions, obstacles etc.) from within the site. Furthermore, the government also sets a required total megawatt production of the site. To facilitate easy maintenance, there is always only one type of turbine at each site, resulting in a predetermined number of turbines to reach the required megawatt production.

NP-hardness

The WFLO problem can be proven to be NP-hard by making an analogy with the P-Dispersion Sum Problem (PDSP) [97]. In the PDSP the goal is to maximise the sum distance between *p* facilities at some *n* predefined locations.in the WFLO we try to maximise the distances between the wind turbines, making it at least the same complexity as the PDSP.

3.1.2. Continuous Methods

In contrast to the discrete approach, the continuous approach does not split the wind farm site into discrete subsections, but treats the wind farm site as one continuous plane. This results in an infinite amount of decision variables and thus novel techniques to solve this problem. It may also result in a higher production, since the turbines locations are not limited to a predefined set. However, frequently, the computational time needed for continuous techniques significantly surpasses that of discrete techniques, making it not the preferred approach in the industry.

Notable Methods

In [6] a **greedy method** is discussed, where three possible moves are defined: Adding, removing or moving a turbine. Although resulting in feasible solutions, it is limited to a few turbines and depended on a grid-like starting point for the optimisation process.

In [37] a continuous approach is taken using **(Continuous) Ants Colony Optimisation**, where the quality of a turbines' location will be quantified by a pheromone value, which in turn determines how many ”ants” will try to randomly assign a new position to said turbine. A similar approach was used in [25] where **Constrained Particle Swarm Optimisation** was implemented.

In contrary to the above single-objective methods, in [76] a bi-objective **Evolutionary Algorithm** is used. While the solution cannot be ensured to be a global optimum, the solution quality is sufficient for industry purpose. In [125] this study is expanded with another continuous bi-objective **Evolutionary Algorithm**, but now focusing on maximising energy production while minimising noise propagation.

An interesting vision is that the above-mentioned methods (with exception from the greedy method) might profit from the increase in knowledge on artificial intelligence, as analysed in [54].

Gradient-based Methods

A significant part of all the continuous methods, are the gradient-based methods. These methods try to exploit Computational Fluid Dynamics, making use of non-linear solver so that induced wake can more accurately be determined. More information on wake models can be found in subsection 2.2.2.

A disadvantage of the gradient-based methods is that their local search algorithms and therefore more likely to end in local optima [21]. Furthermore, most methods fail to incorporate a way of handling obstacles and complex boundaries.

A promising method is written by [58], where a gradient technique is used to exactly optimise the layout of a wind farm up to 100 turbines, also proposing a way of including boundaries. Also, Risco [29], developed a way to process obstacles in a gradient-based optimisation method. Showing promises in the development of this field.

Another advantage of gradient-based algorithms, is the ability to include active control in the optimisation. A subject that is of increasing interest in the offshore wind research field. Active control tries to actively steer the wake to increase production.

Concluding, the continuous methods show some promise and might become more practical in the future. But for now, the methods are computationally heavy and show little adaptation to complex situation, which often times do occur in industry. Lastly, continuous methods are only considered in 2D-space, a plane, where in real life the depth plays a big role in a lot of practical offshore WFLOP methods. For instance, the foundation cost of bottom-fixed turbines, or mooring line length of floating turbines.

3.1.3. Discrete Methods

By discretising the wind farm site, a trade-off is required between solution quality and computational effort. A thinner grid will increase the quality of the solution, but also substantially increase computation time [84]. Within the current discrete methods, a clear distinction can be made between exact and heuristic strategies.

Exact Strategies

Exact strategies solve a mixed integer programming model. These models reach a global optimum, but are also computationally expensive to solve. The amount of turbines, and the number of positions to consider, increases the problem size steeply, creating numerous variables. These approaches are therefore generally limited by the commercial solvers used to solve them.

Different strategies have been explored to reach an exact solution. Donovan [31] designed a **Mixed Integer Programming (MIP)** model based on the vertex packing problem. Here, the vertices are the locations where the turbines could be placed, and the edges represent the relation between the turbines. The vertex packaging problem then aims to select the grid points that generate the most power. In [4] a **Mixed Integer Linear Programming (MILP)** model is created, however this strategy is only tested up to 25 turbines.

Also, in [111] a **MILP model** is suggested and a quadratic integer programming strategy is used and tested on a 10 by 10 grid. In [127] a **constraint programming strategy and MIP model** are developed. The maximum of the last problem-solving technique is 400 potential positions.

Generally, in all previous exact strategies, the noticeable fact is that the methods are limited in capability of solving larger instances. An attempt to work around this limitation, [45], results in a proximity search (ad-hoc) heuristic with a **MIP model in a matheuristic approach**. This splits the problem in portions of maximum 2000 available positions, reaching the highest number of available positions considered in exact literature. But unfortunately, also losing global optimality along the way. Some more heuristics strategies are discussed in subsection 3.1.3.

Heuristic Strategies

The other side of the discrete methods are the heuristic solving strategies. Heuristics have the advantage over exact strategies, as they are more easily able to handle bigger problem sizes in a shorter time. On the other hand, heuristic strategies do not provide optimal solution and can end in local optimums, or not even converge, and fail to find a solution. Also, heuristics are sensitive to initial conditions and the quality of the solution provided is hard to evaluate since the optimal solution is not always known.

A well represented subsection of the heuristics strategies are the **Genetic Algorithms**(GA). Mosetti et al.[89] were the first to address the WFLOP and used a **Genetic Algorithm** to solve it. This tactic was later improved by Grady et al. [57] by implementing smaller subpopulations and increasing the number of iterations. Next to that, both Mora[16] and Gonzalez [56] use a Genetic Algorithm to maximise the Net Present Value, respectively excluding and including wake losses.

Additionally, Huang [64] suggests a **Distributed Genetic Algorithm** to increase local search while maintaining the characteristically good global search properties of a Genetic Algorithm. Huang [65] then further improves this with a **Hybrid Distributed Genetic Algorithm**. Combining Genetic Algorithm with a steepest ascent hill-climbing local search algorithm. Aiming to achieve the optimal balance between global search and local search for better results.

In fact, a considerable amount of literature has been created on using the Genetic Algorithm for solving layout optimisation problems, with each piece of work offering unique improvements or specifications over others. For instance, in [13] the Genetic Algorithm is altered to create **CHC with Simulated Annealing**, in [104] a **multi-objective Genetic Algorithm** is created. In [79] a **bi-criteria Genetic Algorithm** is created, where in [87] a bi-level optimisation based on a gradient approach **Genetic Algorithm** is employed. Lastly, Cheng [24] generated a **Nested Genetic Algorithm** to use on a wind farm with different turbine heights.

Next to the Genetic Algorithms, other types of heuristics tactics also has been explored. For instance, a **Monte Carlo** approach is taken in [82] and, more recently, in [7]. The latter combining the Monte Carlo Search Tree with reinforcement learning, showing the benefits of a hybrid version.

Another hybrid study that was created was the combination between **GRASP (Greedy Randomized Adaptive Search Procedure) meta heuristics and Variable Neighbourhood Search**, by [124].

More recently, [5] suggested a three-step variation on the **Particle Swarm Method**, increasing efficiency by 1.95%. The increased efficiency is extra promising since the Particle Swarm Method may profit from an increase in knowledge in artificial intelligence [54], as mentioned before.

Qualitative comparison is limited to two papers. Firstly, [35], compares a 20 by 20 grid and argues the combination of **Genetic Algorithm and greedy heuristics** is the best option. Secondly, [101], compares some novel methods not discussed in this literature review and concludes **Water Cycle Algorithm** as best.

3.1.4. Summary

The WFLO can be solved with a continuous and discrete approach. Within the continuous methods, a gradient-based approach is most popular. However, continuous method, is computationally heavy and struggles to incorporate obstacles. On the other hand, continuous methods might profit from recent advancements in Artificial Intelligence technology.

Discrete methods are most often used in industry. Exact methods can be used, but are often times too computationally expensive and thus heuristics are used. Heuristics can, however, end in a local optimum. The best results are obtained by using a genetic algorithm, possibly combined with a greedy approach.

3.2. Wind Farm Cable Routing Problem

In this section, the Wind Farm Cable Routing (WFCR) problem will be explained and an overview of the literature will be offered. First, the problem will be introduced. Second, an overview of the discrete methods will be presented. Finally, a summary of the discussed literature will be given.

3.2.1. Problem Introduction

The WFCR problem aims to minimise electrical infrastructure CAPEX cost while maintaining a sufficient and safe transfer of power between the wind turbines and the main substation [18], also called an inter-array connection, see section Figure 2.2.1.

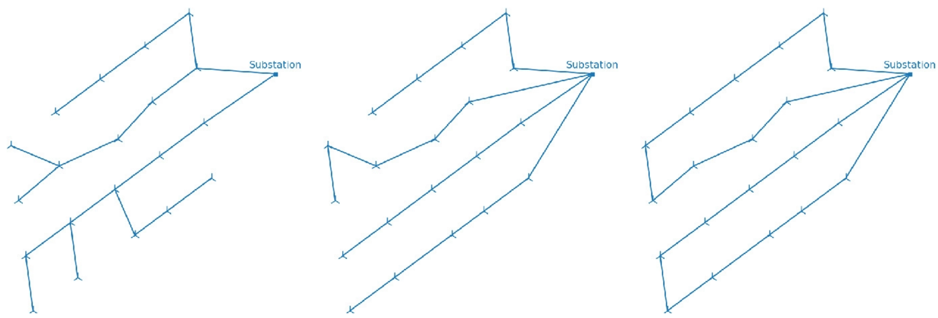
To decrease costs of O&M and meet safety standards, cables are not allowed to cross over or under each other [62]. Also, there are different cable sizes available. Each cable has their own maximum electrical capacity and cost.

NP-hardness

The WFCR problem can be proven to be NP-hard by making the analogy with the Weight Constrained Graph Tree Partition Problem (WGTPP) [50]. It even remains NP-hard when making simplifications by assuming that the nodes are located in a two-dimensional plane and that the cost of laying cable depends only on the Euclidean distance between nodes. Also, in the above case, only one substation is considered, but as explained in Figure 2.2.1, that is often not the case, increasing the complexness of the problem.

Inter-array Topology

In general, three main topological configurations have been considered concerning the inter-array electrical connection. These topological configurations are depicted in Figure 3.1.



(A) (B) (C)

Figure 3.1: A: Branched, B: Radial, C: Looped. Three main topological configurations concerning the inter-array cable layout, retrieved from [19].

A branched layout allows for multiple cables to enter the turbine, but for only one to exit the turbine. A radial layout allows for only one cable to enter the turbine, and for only one cable to exit the turbine. Finally, a looped layout allows for only one cable to enter the turbine and for one cable to exit the turbine, but allowing to loop back into other "strings". This introduces redundancy in the system, decreasing the potential downtime of every wind turbine, which is in turn increases the efficiency of the turbine [41].

If every cable leaving the substation connects the same amount of turbines, this configuration is called balanced. Of course, this can differ by at most one, in the case of a remaining turbine when equally dividing them onto the 'strings'. The balanced configuration is the standard in the industry. Firstly, it is more cost-effective [19], but next to that, a balanced network allows for the transformers in the substations to be universal trough out the whole farm [2]. This means that in case of failure, an on-site back-up can quickly be installed. Also, by evening out the wear over all the transformers equally, the costs of spare components and of maintenance in case of failures are kept to a minimum [19]. Thus far, only Cazzarro [19] considers a balanced cable layout.

Continuous Approach

A continuous approach is not considered in the WFCR problem. This is because of the practical reasoning that unconventional bends in cables are not feasible. Straight lines with clear bends are preferred, and thus discretising of the plane is preferred.

However, when the power losses in the cables are considered, a continuous decision variable can be chosen to represent the flow in the cables, as can be seen in [48].

3.2.2. Discrete Methods

Mixed Integer Linear Programming

A basic MILP model is described by Fischetti and Pisinger [50], this model is then solved exactly and with the help of matheuristics [43]. This basic model makes use of Steiner-nodes to allow for bent cables and account for obstacles. A considerable amount of papers expanded that basic model: In [48] power losses within the cables are accounted for, in [47] closed loop structures are imposed and branching is penalised. Furthermore, in [44], Fischetti uses it together with layout optimisation to sequentially optimise the allocation of wind turbines.

Next to that, another MILP model is proposed in [40]. And lastly, Hertz [60], proposed a Mixed Integer Quadratic model to model the network design. It was subsequently linearized to make it easier to solve.

Heuristic Methods

Since basic MILP formulations cannot be solved in reasonable time for difficult instances, different heuristic algorithms are often consulted.

Extending the basic MILP formulation, in [46] three matheuristics approaches are developed. Namely, **random fixing**, **distance based fixing** and **sector fixing**. By first relaxing restraining constraints, allowing the model to quickly find a first solution, and then using the three aforementioned matheuristics to keep the number of variables at a minimum, the model is allowed to solve for large, real world, wind farms. Later, Fischetti [49] expanded that model for radial and looped instances.

Bauer and Lysgaard [9] compare the WFCR problem to the vehicle routing problem and develop a **planar open savings heuristic** based on the Clarke and Wright savings heuristic [27]. This strategy is later expanded by [72] and compared to **Esau-Williams**. Results show that especially the location of the substation influences the outcome of this comparison. The substation can be placed centrally or outside the farm area. Later, El Mokhi [34] found that a centrally placed substation is preferable.

In [71] an **adaptive particle swarm optimisation** algorithm is used, in an attempt to avoid local minima, recognising the non-convexity of the problem. This algorithm is complemented with a **stochastic spanning tree**, namely a minimum spanning tree. Zuo et al. [128] also makes use of a minimum spanning tree (Prim's algorithm [98]) but starts the optimisation with a **Fuzzy C-means clustering method**.

In [70], Jenkins concluded that branched networks are favourable over radial networks, but not enforcing a balanced constraint to the network design. This conclusion is made by first using a **Greedy algorithm** for the initial solution and using a **Genetic algorithm** for the optimisation. [123] also uses the **Greedy algorithm** combined with the **Genetic algorithm**, but accounts for obstacles by the use of exclusion zones and visibility graphs (see subsection 3.2.2).

Lastly, Cazzaro et al. [18] compared six heuristic method for an unbalanced scenario and determines **Variable Neighbourhood Search** as the best. **Tabu Search** also showed good results, but is less easy to tune and implement. Following, Cazzaro et al. [19] presented the only balanced cable routing heuristic, making use of **Large Neighbourhood Search**, and a **Sweep algorithm** to generate a set of initial solutions.

External Obstacles

With the increasing amount of offshore wind farms and other infrastructure, obstacle free locations are becoming more and more scarce. This means that the ability to model obstacles in the routing of cables is becoming of greater interest. However, not many papers consider obstacles yet.

Because of the decrease in spatial resolution and the introduction of unwilling right angles, grid based obstacle avoidance methods are avoided when used solely. Examples of grid based obstacle avoidance methods are A*-path finding and Dijkstra's Algorithm. Grid based obstacle avoidance methods, however, can be used in combinations with other novel techniques to find the shortest path along some obstacle free paths.

In [96], obstacles are avoided by the use of Delaunay Triangulation and navigational mesh based path finding. In this paper, released in 2015, it is also stated that avoiding obstacles by the use of a visibility graph is too computationally expensive. A visibility graph constructs a graph for every vertex that is visible to other vertices, and thus not blocked by an obstacle.

However, in more recent papers [19] & [123] a visibility graph is used to avoid obstacles, suggesting that the computational expenditure is covered by faster computers, since the used algorithm dates from 2008 [11]. After the visibility graph is created, Dijkstra's Algorithm is used to compute the shortest path.

Next to the visibility graph, Fischetti et al. [46] developed a technique with the use of Steiner nodes, a technique later improved by Klein et al.[74], making it an optimal approach.

3.2.3. Summary

For the WFCR problem, continuous methods are infeasible because non-conventional bends are not preferred in cable routing. For discrete methods, heuristics methods are the most popular. A combination of a genetic algorithm with a greedy approach is often used, but Variable Neighbourhood Search also shows great potential. To implement obstacles, a visibility graph or Steiner nodes can be used.

3.3. Unified Approach

In the unified approach, both the WFLO and the WFCR are solved in one combined, simultaneous optimisation. In this section, an overview of this approach will be offered. At first, an introduction will be given to the problem. After that, some methods used will be discussed. And finally, a summary will be given, on the best way to approach a unified optimisation.

3.3.1. Problem Introduction

WFLO and WFCR have contradictory goals. Where it is beneficial for the lay-out optimisation to space turbines as far apart as possible and thus decrease wake effects, it is beneficial for the cable routing to place the turbines close to each other and thus decrease cable length. This means that a unified approach will lead to a decrease in life-time energy yield of the wind farm, but also a decrease in CAPEX, specifically the cable costs.

3.3.2. Methods

The unified problem is solved for onshore instances in [55] as a cost model. Here, the cumulative net cash flow presents the value of the wind farm's whole life span. The cost model is then solved with two nested **Evolutionary Algorithms(EA)**, where the main EA calculates the layout and controls the secondary EA, where the electrical infrastructure is optimised.

In [121] it is decided to use a **Genetic Algorithm (GA)** for the WFLO and an **Ant Colony System (ACS)** algorithm for the WFCR. The ACS calculates a fitness value and this will be fed back to the GA. Then trough replication, crossover and mutation an optimal wind farm layout can be obtained. GA is also used in [100], but it is used sequentially with **linear programming**. In this paper, the grid is increasingly narrowed trough out a multi-fidelity approach to achieve greater results. Another approach where GA is used is [120], but here **GeoSteiner** is used for the WFCR instead of ACS. An overview of how GA mutates in this algorithm can be found in Figure 3.2.

Another interesting approach is presented in [109]. This approach opted to use a **bi-level multi-objective framework**. It is constructed with one outer layer, with the objective of maximisation of the wind farm's daily profit rate, which is solved by **Non-dominated Sorting Genetic Algorithm-III (NSGA-III)**. Next to that, an inner layer entails the WFCR by using the **Binary Particle Swarm Optimisation**

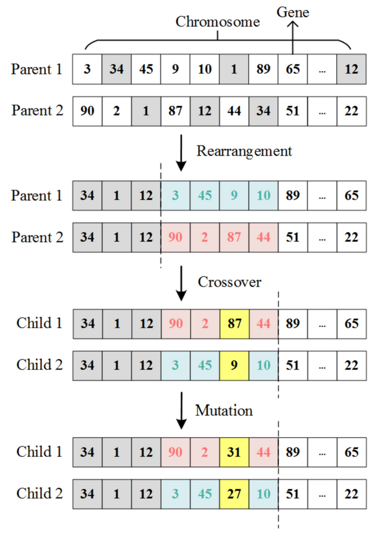


Figure 3.2: Overview of different mutation strategies, retrieved from [120].

(BPSO) algorithm. In this paper, it is stated that the joint optimisation is favourable over an independent approach.

A continuous approach is considered in [63] and [94]. Respectively, using an **Adaptive Particle Swarm Optimisation** and a **Random Search** for WFLO and a **Fitness Evaluation** algorithm and a **MILP** model for WFCR.

Please note that the techniques discussed thus far have only been tested on small, non-industry, instances. Two papers that have considered industry size wind farms, are Cazzarro et al. [20] and Fischetti [42]. Cazzarro construct a joint MILP formulation. This is then solved using a **Variable Neighbourhood Search (VNS)**, which modifies the turbine locations and the cable routing solution simultaneously. Fischetti also constructs a joint MILP model, which is then solved using **Benders-like cuts** that are derived from an induced-clique substructure. Next to these cuts, an exact **Branch-and-cut** solver is used for the problem.

3.3.3. Summary

With the use of a unified approach of the WFLO and WFCR, the LCOE decreases. Effectively, the CAPEX is decreased while the life-time energy yield is slightly decreased. A Genetic Algorithm is often times used for this problem, but not capable of considering larger, realistic, instances used in industry. Variable Neighbourhood Search is the better algorithm for this purpose, although having a long run time. This is assumed not impactful since WFLO and WFCR are offline solved problems, where run time is of lesser importance.

4

Floating Offshore Wind Farm Optimisation & Relevant Problems

The research done on the optimisation of floating offshore wind farms is very scarce, and focuses on active control optimisation. Here, the flexibility in turbine location is exploited to intently steer the turbine out of a wake. These ideas are however far away from practical execution and are not in the scope of this research. Within the scope of this research, optimising a floating offshore wind farm for anchor sharing and cable routing, no research has been done yet.

Firstly, the two problems revolving around our thesis will be explained. Starting with anchor sharing, where the goal is to minimise the amount of anchors or maximise the amount of shared anchors. After that, the cable routing problem will be explained, where the goal is to minimise the cable cost.

Because no research has been done yet on these two problems, it is essential to explore similar problems and frame our problem more towards similar problems. This will be done in the last subsection of both problems.

4.1. Anchor sharing

4.1.1. Problem Introduction and Challenges

As explained before, offshore wind farms will be placed at locations where the water depths are greater. This means that the anchor placement cost can increase significantly. To reduce the amount of anchors in the wind farm, it is possible to attach multiple mooring lines to one anchor, and thus reducing the amount of anchors used. Connolly and Hall [28] have found that in depths deeper than 400 meters, which are depths that are targeted with floating offshore wind farms, a significant cost saving can be achieved by sharing anchors.

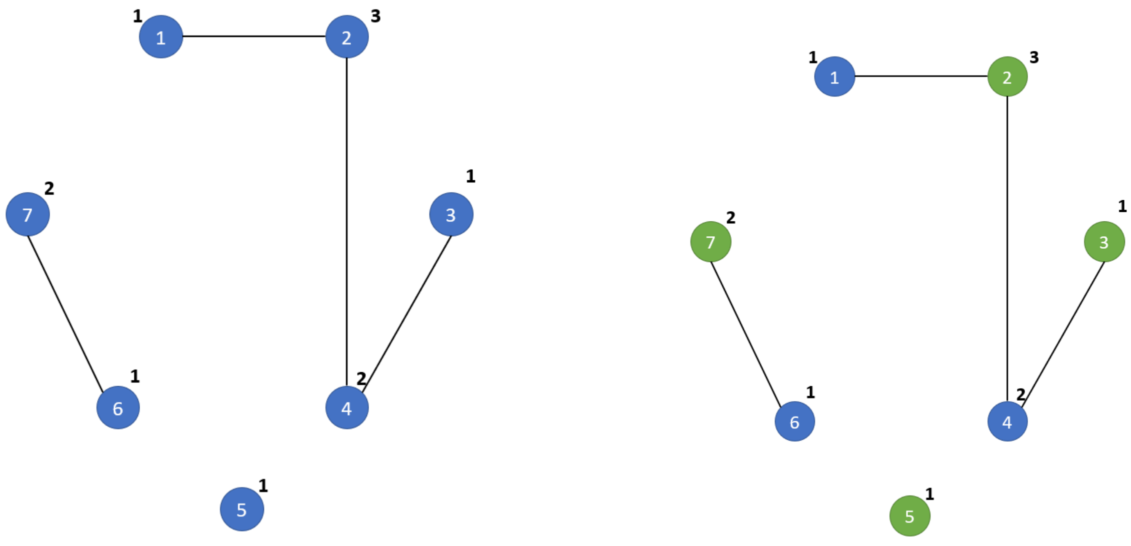
So we would like to share as many anchors as possible. A geometrical pattern would quickly arise as an optimal layout. However, the optimised layout solved by the WFLOP, as described in section 3.1, would be lost. Furthermore, with obstacles occurring in the site, the layout would be infeasible.

4.1.2. Similar Problems

Graph Theory

The problem can be analysed using a graph theory perspective. This theory makes use of graphs to represent relations between objects. Where an object and a relation between two objects are respectively represented by nodes and edges. Often times there are weights attached to nodes or edges. A useful subsection of graph theory, would be the **Maximum Weighted Independent Set Problem**. In this problem, a weighted graph is subdivided in an as heavily weighted sub-graph as possible, without any of the selected nodes sharing vertices. In this problem, two nodes share a vertex if they share a dependence with each other. An overview is given in Figure 4.1.

In our case, for every design option for every turbine, a node would be created. If one or more mooring lines of a design cross with another design, an edge between those two designs is created, representing the conflicting relation between these two designs. With this technique, a wind farm is



(a) Total graph with weights in black next to the node, vertices represent a relation.

(b) Sub-graph that represents the maximum weighted independent set.

Figure 4.1: Maximum weighted independent set problem

guaranteed to not have conflicting design, but not to share anchors. If the weights of the nodes represent the amount of anchors the design shares, there is no relation between the two designs. Meaning, if one design is not picked, there is no way of knowing for the other design. A better alternative would be to define positive and negative relations between nodes, where positive relations equals anchors being shared, and negative relations equals conflicting designs. The goal would then become to create as large groups as possible, without including negative relations.

Signed Networks

An interesting use case, where both positive and negative relations are used in graph theory, are signed networks. Signed networks are often used to describe social networks and interactions. Where a positive relation can be compared with a friendship and a negative relation with a hostile relation. In the case of anchor sharing, a negative relation between two design would still equal conflicting design. A positive relation between two designs would equal the fact that the designs will be sharing anchors. An overview of a signed network is pictured in Figure 4.2, where it is visible that sub graphs can be constructed with just positive relations. However, signed network theory focuses on balancing the graph. This means that every sub graph contains an even amount of negative relations. In the case of anchor sharing, we would like to maximise the amount of positive relations without introducing any negative relations. This is an objective that is unknown for signed networks.

4.2. Cable Routing

4.2.1. Problem Introduction and Challenges

The cable routing for floating offshore wind farms does not differ by much in comparison with fixed-bottom offshore wind farms. In the new situation, also every turbine needs to be connected with a substation, while minimising the cost of this cable layout. However, because of safety reasons, it is forbidden to place power cables above or below mooring lines. This induces an extra constraint, which could be viewed similarly as how an obstacle is considered in the WFCR problem. But because we also optimise for as much anchor sharing as possible, an interesting problem arises. We would not want to share anchors, to leave space for cables, so that they are able to pass between mooring lines and connect turbines. This is where the true essence of our thesis problem reveals itself. To create a layout whereas many anchors as possible are shared, while also minimising the cable cost.

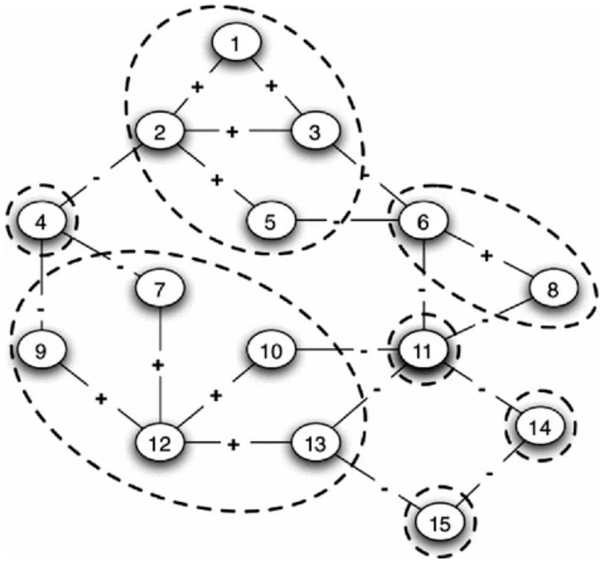


Figure 4.2: A signed network with positive and negative relations depicted. Sub graphs with just positive relations are circled by dashes. Retrieved from [99].

4.2.2. Similar Problem

Wind Farm Cable Routing Problem

The conventional cable routing for fixed-bottom turbines is very similar and can most likely be used to a great extent. An extensive overview of this problem is given in section 3.2. An additional constraint must however be added; A power cable is not allowed to cross over or under a mooring line. This is also to ensure safe and cheap O&M cost. Just as is the case with crossing over or under other power cables.

Next to that, in [78] Lerch optimises the electrical layout for floating offshore wind farms. However, the cable routing is not a part of this. In this paper, Lerch focuses on the difference between dynamic and static power cables and what type of cable is best used. Also, the layout of the turbines and substation is given, and no obstacles are taken into account.

5 Conclusion

This literature review critically identifies and fills a significant research gap in the optimisation strategies for floating offshore wind farms (FOWFs). This chapter aims to conclude the findings of the literature reviewed in this study.

Because of several disadvantages, countries are moving away from fossil fuels and shifting more and more focus towards renewable energy. Offshore wind shows great potential to grow, and will probably be part of the hybrid collection of renewable energy sources of the future. The quest to lower the levelised cost of energy (LCOE) of offshore wind energy, by decreasing the cost and increasing the energy revenue, has driven developers towards innovative mathematic layout optimisation of offshore wind farms.

72% of the global offshore wind resource capacity is located in waters too deep for bottom-fixed wind turbines. Floating wind turbines offer a welcome solution for harnessing these deep-water wind resources. However, with floating wind being a new technology, and still in development, it is not yet cost advantageous. The master thesis accompanying this literature study aims to optimise the layout of offshore floating wind farms to decrease cost and with that minimise the LCOE of offshore floating wind. The following research question is sought to be answered: *What is the best strategy for minimising the amount of anchors while also minimising the power cable cost, when designing the layout of a floating offshore wind farm?*

In chapter 2, the need for offshore wind is discussed. It is concluded that offshore wind shows great potential and will most probably grow into our future energy production system as a permanent member. Current technology in offshore wind farms are well-developed, but floating offshore wind entails more uncertainty in the design process. The wake modelling, anchoring type and inter-array cable types have not reached consensus over industry, and it is still uncertain what a standard floating wind farm will look like. From this chapter it can also be concluded that the CAPEX cost is the best criteria for determining the success of the layout design of an offshore wind farm. This is because the NPV also takes revenue into account, and this is not influenced by anchor sharing or cable routing.

In chapter 3, the different optimisation techniques used in designing the layout of offshore wind farms are discussed. For the Wind Farm Layout Optimisation (WFLO) problem, it can be concluded that a discrete approach is best for practical industry purposes. Also, a heuristic approach is preferable because of the fast computation time while maintaining solution quality. The best results can be obtained by using a genetic algorithm, possibly combined with a greedy approach. These techniques can be adopted from the WFLO heuristic. It is also possible to use the output from a created WFLO model for an optimised turbine location layout for floating offshore wind farms. This because the planar location of a wind turbine is irrelevant of the foundation method. Nonetheless, it is important to acknowledge that the wake generated by a floating wind turbine behaves differently, which necessitates caution when directly applying a layout of a bottom-fixed wind farm to a floating wind farm.

Also, the Wind Farm Cable Routing (WFCR) problem is discussed. From literature, it can be concluded that a combination of a genetic algorithm with a greedy approach is often used, but Variable Neighbourhood Search also shows great potential. To implement obstacles, a visibility graph or Steiner nodes can be used. It is expected that a lot of these techniques can be adopted for implementation of our floating offshore wind model.

Finally, a Unified optimisation of the WFLO and WFCR is also discussed in chapter 3. An advantage of using the Variable Neighbourhood Search in the WFCR is that it can be used in the Unified approach, where a genetic algorithm is not capable of handling larger scenarios. It can thus be concluded from literature that Variable Neighbourhood Search can be beneficial for combining multiple goals in wind farm layout design.

In chapter 4, current literature on floating wind farm optimisation is discussed. Literature is scarce on this subject, leading to a need to explore other research areas for potential overlapping solutions. The best strategy to minimise the power cable cost according to literature would be to implement Variable neighbourhood search in combination with a visibility graph. Different strategies can be explored to minimise the amount of anchors, namely solving it as a MILP model and solving it as a graph theory model.

This literature study identified a significant research gap in the optimisation strategies of the lay-out of floating offshore wind farms (FOWFs).Transferring methods directly from bottom-fixed wind farm optimisation is insufficient, demanding new optimisation techniques specifically for FOWFs. Therefore, this literature study emphasises the need for innovative solutions to unique challenges such as cable routing and anchor sharing. According to this literature review, Net Present Value (NPV) stands out as the most reliable metric for assessing the success of FOWF optimisation strategies. With respect to solution methods, a Variable Neighbourhood Search (VNS) integrated with a visibility graph is particularly promising for the Wind Farm Cable Routing (WFCR) problem, offering flexibility in accommodating multiple objectives and handling obstacles. The thesis should further investigate various strategies for anchor optimisation, exploring both Mixed-Integer Linear Programming (MILP) and graph theory models. These conclusions highlight the pressing need for dedicated research into FOWF optimisation strategies, which can significantly enhance the literature and lead to more economically viable renewable energy solutions.

References

[1] M. S. Adaramola and P. Å Krogstad. “Experimental investigation of wake effects on wind turbine performance”. In: *Renewable Energy* 36 (8 Aug. 2011), pp. 2078–2086. ISSN: 0960-1481. DOI: 10.1016/J.RENENE.2011.01.024.

[2] Samir Milad Alagab, Sarath Tennakoon, and Chris Gould. “Review of wind farm power collection schemes”. In: *2015 50th International Universities Power Engineering Conference (UPEC)*. 2015, pp. 1–5. DOI: 10.1109/UPEC.2015.7339922.

[3] Tze-Zhang Ang et al. “A comprehensive study of renewable energy sources: Classifications, challenges and suggestions”. In: *Energy Strategy Reviews* 43 (2022), p. 100939. ISSN: 2211-467X. DOI: https://doi.org/10.1016/j.esr.2022.100939. URL: https://www.sciencedirect.com/science/article/pii/S2211467X2200133X.

[4] Rosalind Archer et al. “Wind Turbine Interference in a Wind Farm Layout Optimization Mixed Integer Linear Programming Model”. In: *Wind Engineering* 35 (Apr. 2011), pp. 165–175. DOI: 10.1260/0309-524X.35.2.165.

[5] Philip Asaah, Lili Hao, and Jing Ji. “Optimal Placement of Wind Turbines in Wind Farm Layout Using Particle Swarm Optimization”. In: *Journal of Modern Power Systems and Clean Energy* 9.2 (2021), pp. 367–375. DOI: 10.35833/MPCE.2019.000087.

[6] U Aytun Ozturk and Bryan A Norman. “Heuristic methods for wind energy conversion system positioning”. In: *Electric Power Systems Research* 70.3 (2004), pp. 179–185. ISSN: 0378-7796. DOI: https://doi.org/10.1016/j.epsr.2003.12.006. URL: https://www.sciencedirect.com/science/article/pii/S0378779603003043.

[7] Fangyun Bai et al. “Wind farm layout optimization using adaptive evolutionary algorithm with Monte Carlo Tree Search reinforcement learning”. In: *Energy Conversion and Management* 252 (2022), p. 115047. ISSN: 0196-8904. DOI: https://doi.org/10.1016/j.enconman.2021.115047. URL: https://www.sciencedirect.com/science/article/pii/S0196890421012231.

[8] F. Barbir, T.N. Veziro□lu, and H.J. Plass. “Environmental damage due to fossil fuels use”. In: *International Journal of Hydrogen Energy* 15.10 (1990), pp. 739–749. ISSN: 0360-3199. DOI: https://doi.org/10.1016/0360-3199(90)90005-J. URL: https://www.sciencedirect.com/science/article/pii/036031999090005J.

[9] Joanna Bauer and Jens Lysgaard. “The offshore wind farm array cable layout problem: a planar open vehicle routing problem”. In: *Journal of the Operational Research Society* 66.3 (2015), pp. 360–368.

[10] Philipp Beiter et al. *The cost of floating offshore wind energy in California between 2019 and 2032*. Tech. rep. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2020.

[11] Md Berg et al. “Computational geometry: Algorithms and applications. 2008”. In: *Google Scholar Google Scholar Digital Library Digital Library* (2008).

[12] Vasishta Bhargava and Rahul Samala. “Acoustic emissions from wind turbine blades”. In: *Journal of aerospace technology and management* 11 (2019).

[13] Martín Bilbao and Enrique Alba. “CHC and SA applied to wind energy optimization using real data”. In: *IEEE Congress on Evolutionary Computation*. 2010, pp. 1–8. DOI: 10.1109/CEC.2010.5586395.

[14] Nicolas Boccard. “Capacity factor of wind power realized values vs. estimates”. In: *Energy Policy* 37.7 (2009), pp. 2679–2688. ISSN: 0301-4215. DOI: https://doi.org/10.1016/j.enpol.2009.02.046. URL: https://www.sciencedirect.com/science/article/pii/S030142150900144X.

[15] Christoph Breidert, Michael Hahsler, and Thomas Reutterer. “A review of methods for measuring willingness-to-pay”. In: *Innovative marketing* 2.4 (2006).

[16] José Castro Mora et al. “An evolutive algorithm for wind farm optimal design”. In: *Neurocomputing* 70.16 (2007). Neural Network Applications in Electrical Engineering Selected papers from the 3rd International Work-Conference on Artificial Neural Networks (IWANN 2005), pp. 2651–2658. ISSN: 0925-2312. DOI: https://doi.org/10.1016/j.neucom.2006.05.017. URL: https://www.sciencedirect.com/science/article/pii/S0925231207000914.

[17] Davide Cazzaro. “Unified Optimization for Offshore Wind Farm Design”. Supervised by Prof. David Pisinger; Industrial Supervisors: Dr. David Franz Koza and MSc.EE Jesper Runge Kristoffersen from Vattenfall Vindkraft A/S. Industrial Ph.D. Thesis. Akademivej, Building 358, DK-2800 Kgs. Lyngby: Technical University of Denmark, DTU Management, Management Science, Aug. 2022.

[18] Davide Cazzaro, Martina Fischetti, and Matteo Fischetti. “Heuristic algorithms for the wind farm cable routing problem”. In: *Applied Energy* 278 (2020), p. 115617.

[19] Davide Cazzaro, David Franz Koza, and David Pisinger. “Balanced and unbalanced networks in offshore wind farms”. In: *11th Triennial Symposium on Transportation Analysis conference*. 2022.

[20] Davide Cazzaro, David Franz Koza, and David Pisinger. “Combined layout and cable optimization of offshore wind farms”. In: *European Journal of Operational Research* (2023).

[21] Davide Cazzaro and David Pisinger. “Variable neighborhood search for large offshore wind farm layout optimization”. In: *Computers & Operations Research* 138 (2022), p. 105588.

[22] Srinivasan Chandrasekaran. *Dynamic analysis and design of offshore structures*. Vol. 761. Springer, 2015.

[23] Jiandong Chen et al. “Global non-fossil fuel consumption: driving factors, disparities, and trends”. In: *Management Decision* 57.4 (2019), pp. 791–810.

[24] Ying Chen et al. “Wind farm layout optimization using genetic algorithm with different hub height wind turbines”. In: *Energy Conversion and Management* 70 (2013), pp. 56–65. ISSN: 0196-8904. DOI: https://doi.org/10.1016/j.enconman.2013.02.007. URL: https://www.sciencedirect.com/science/article/pii/S0196890413000873.

[25] Souma Chowdhury et al. “Unrestricted wind farm layout optimization (UWFLO): Investigating key factors influencing the maximum power generation”. In: *Renewable Energy* 38.1 (2012), pp. 16–30. ISSN: 0960-1481. DOI: https://doi.org/10.1016/j.renene.2011.06.033. URL: https://www.sciencedirect.com/science/article/pii/S0960148111003260.

[26] THOMAS BO CHRISTENSEN. Nov. 2016. URL: https://energywatch.com/EnergyNews/Renewables/article9166785.ece.

[27] Geoff Clarke and John W Wright. “Scheduling of vehicles from a central depot to a number of delivery points”. In: *Operations research* 12.4 (1964), pp. 568–581.

[28] Patrick Connolly and Matthew Hall. “Comparison of pilot-scale floating offshore wind farms with shared moorings”. In: *Ocean Engineering* 171 (2019), pp. 172–180.

[29] J. Criado Risco et al. “Gradient-based Wind Farm Layout Optimization With Inclusion And Exclusion Zones”. In: *Wind Energy Science Discussions* 2023 (2023), pp. 1–24. DOI: 10.5194/wes-2023-5. URL: https://wes.copernicus.org/preprints/wes-2023-5/.

[30] H. Díaz and C. Guedes Soares. “Review of the current status, technology and future trends of offshore wind farms”. In: *Ocean Engineering* 209 (2020), p. 107381. ISSN: 0029-8018. DOI: https://doi.org/10.1016/j.oceaneng.2020.107381. URL: https://www.sciencedirect.com/science/article/pii/S002980182030411X.

[31] Stuart Donovan. “Wind Farm Optimization”. In: 2005.

[32] Katherine Dykes. “Optimization of wind farm design for objectives beyond LCOE”. In: *Journal of Physics: Conference Series*. Vol. 1618. 4. IOP Publishing. 2020, p. 042039.

[33] A EC. “Clean Planet for all: a European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy”. In: *COM (2018) 773-COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE, THE COMMITTEE OF THE REGIONS AND THE EUROPEAN INVESTMENT BANK* (2018).

[34] Chakib El Mokhi and Adnane Addaim. “Optimal Substation Location Of A Wind Farm Using Different Metaheuristic Algorithms”. In: *2020 IEEE 6th International Conference on Optimization and Applications (ICOA)*. 2020, pp. 1–6. DOI: 10.1109/ICOA49421.2020.9094469.

[35] Christopher Elkinton, James Manwell, and Jon Mcgowan. “Algorithms for Offshore Wind Farm Layout Optimization”. In: *Wind Engineering* 32 (Jan. 2008), pp. 67–84. DOI: 10.1260/030952408784305877.

[36] Peter Enevoldsen and Scott Victor Valentine. “Do onshore and offshore wind farm development patterns differ?” In: *Energy for Sustainable Development* 35 (2016), pp. 41–51. ISSN: 0973-0826. DOI: https://doi.org/10.1016/j.esd.2016.10.002. URL: https://www.sciencedirect.com/science/article/pii/S0973082616308146.

[37] Yunus Eroğlu and Serap Ulusam Seçkiner. “Design of wind farm layout using ant colony algorithm”. In: *Renewable Energy* 44 (2012), pp. 53–62. ISSN: 0960-1481. DOI: https://doi.org/10.1016/j.renene.2011.12.013. URL: https://www.sciencedirect.com/science/article/pii/S096014811100694X.

[38] Stepping Up Europe’s. “2030 Climate Ambition—Investing in a Climate-Neutral Future for the Benefit of Our People”. In: *European Commission: Luxembourg* 53 (2020).

[39] *Factsandfigures*. Aug. 2022. URL: https://www.northfallsoffshore.com/facts-figures/ (visited on 03/08/2023).

[40] Patrik Fagerfjäll. “Optimizing wind farm layout: more bang for the buck using mixed integer linear programming”. 2010.

[41] Stefan Faulstich, Berthold Hahn, and Peter J Tavner. “Wind turbine downtime and its importance for offshore deployment”. In: *Wind energy* 14.3 (2011), pp. 327–337.

[42] Martina Fischetti and Matteo Fischetti. “Integrated Layout and Cable Routing in Wind Farm Optimal Design”. In: *Management Science* 69.4 (2023), pp. 2147–2164.

[43] Martina Fischetti and Matteo Fischetti. “Matheuristics”. In: *Handbook of heuristics*. Springer, 2018, pp. 121–153.

[44] Martina Fischetti, Matteo Fischetti, and Michele Monaci. “Optimal Turbine Allocation for Offshore and Onshore Wind Farms”. In: Jan. 2016, pp. 55–78. ISBN: 978-4-431-55419-6. DOI: 10.1007/978-4-431-55420-2_4.

[45] Martina Fischetti and Michele Monaci. “Proximity search heuristics for wind farm optimal layout”. In: *Journal of Heuristics* 22 (2016), pp. 459–474.

[46] Martina Fischetti and David Pisinger. “Inter-array cable routing optimization for big wind parks with obstacles”. English. In: *Proceedings of the 2016 European Control Conference (ECC)*. 15th European Control Conference, ECC16 ; Conference date: 29-06-2016 Through 01-07-2016. United States: IEEE, 2016, pp. 617–622. DOI: 10.1109/ECC.2016.7810357. URL: http://www.ecc16.eu/call.shtml.

[47] Martina Fischetti and David Pisinger. “Mixed Integer Linear Programming for new trends in wind farm cable routing”. In: *Electronic Notes in Discrete Mathematics* 64 (2018). 8th International Network Optimization Conference - INOC 2017, pp. 115–124. ISSN: 1571-0653. DOI: https://doi.org/10.1016/j.endm.2018.01.013. URL: https://www.sciencedirect.com/science/article/pii/S1571065318300131.

[48] Martina Fischetti and David Pisinger. “On the impact of considering power losses in offshore wind farm cable routing”. In: *Operations Research and Enterprise Systems: 6th International Conference, ICORES 2017, Porto, Portugal, February 23–25, 2017, Revised Selected Papers 6*. Springer. 2018, pp. 267–292.

[49] Martina Fischetti and David Pisinger. “Optimal wind farm cable routing: Modeling branches and offshore transformer modules”. In: *Networks* 72.1 (2018), pp. 42–59.

[50] Martina Fischetti and David Pisinger. “Optimizing wind farm cable routing considering power losses”. In: *European Journal of Operational Research* 270.3 (2018), pp. 917–930. ISSN: 0377-2217. DOI: https://doi.org/10.1016/j.ejor.2017.07.061. URL: https://www.sciencedirect.com/science/article/pii/S037722171730704X.

[51] P. Fleming et al. “Continued results from a field campaign of wake steering applied at a commercial wind farm – Part 2”. In: *Wind Energy Science* 5.3 (2020), pp. 945–958. DOI: 10.5194/wes-5-945-2020. URL: https://wes.copernicus.org/articles/5/945/2020/.

[52] Michelle Froese. *Making of the modern offshore substation*. Oct. 2016. URL: https://www.windpowerengineering.com/making-modern-offshore-substation/ (visited on 03/08/2023).

[53] Ibon Galparsoro et al. “Reviewing the ecological impacts of offshore wind farms”. In: *npj Ocean Sustainability* 1.1 (2022), p. 1.

[54] Fausto Pedro García Márquez and Alfredo Peinado Gonzalo. “A comprehensive review of artificial intelligence and wind energy”. In: *Archives of Computational Methods in Engineering* (2021), pp. 1–24.

[55] J. Serrano González et al. “Overall design optimization of wind farms”. In: *Renewable Energy* 36.7 (2011), pp. 1973–1982. ISSN: 0960-1481. DOI: https://doi.org/10.1016/j.renene.2010.10.034. URL: https://www.sciencedirect.com/science/article/pii/S0960148110005495.

[56] Javier Serrano González et al. “Optimization of wind farm turbines layout using an evolutive algorithm”. In: *Renewable Energy* 35.8 (2010), pp. 1671–1681. ISSN: 0960-1481. DOI: https://doi.org/10.1016/j.renene.2010.01.010. URL: https://www.sciencedirect.com/science/article/pii/S0960148110000145.

[57] S.A. Grady, M.Y. Hussaini, and M.M. Abdullah. “Placement of wind turbines using genetic algorithms”. In: *Renewable Energy* 30.2 (2005), pp. 259–270. ISSN: 0960-1481. DOI: https://doi.org/10.1016/j.renene.2004.05.007. URL: https://www.sciencedirect.com/science/article/pii/S0960148104001867.

[58] David Guirguis, David A. Romero, and Cristina H. Amon. “Toward efficient optimization of wind farm layouts: Utilizing exact gradient information”. In: *Applied Energy* 179 (2016), pp. 110–123. ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2016.06.101. URL: https://www.sciencedirect.com/science/article/pii/S0306261916308765.

[59] Muhammad Asif Hanif et al. “Future energy options: an overview”. In: *Renewable and Alternative Energy Resources* (2022), pp. 113–169. DOI: 10.1016/B978-0-12-818150-8.00009-5.

[60] Alain Hertz et al. “Design of a wind farm collection network when several cable types are available”. In: *Journal of the Operational Research Society* 68 (2017), pp. 62–73.

[61] Pablo Hevia-Koch and Henrik Klinge Jacobsen. “Comparing offshore and onshore wind development considering acceptance costs”. In: *Energy Policy* 125 (2019), pp. 9–19. ISSN: 0301-4215. DOI: https://doi.org/10.1016/j.enpol.2018.10.019. URL: https://www.sciencedirect.com/science/article/pii/S030142151830675X.

[62] Peng Hou et al. “A review of offshore wind farm layout optimization and electrical system design methods”. In: *Journal of Modern Power Systems and Clean Energy* 7.5 (2019), pp. 975–986.

[63] Peng Hou et al. “Combined optimization for offshore wind turbine micro siting”. In: *Applied Energy* 189 (2017), pp. 271–282. ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2016.11.083. URL: https://www.sciencedirect.com/science/article/pii/S0306261916317135.

[64] H. S. Huang. “Distributed Genetic Algorithm for Optimization of Wind Farm Annual Profits”. In: *2007 International Conference on Intelligent Systems Applications to Power Systems*. 2007, pp. 1–6. DOI: 10.1109/ISAP.2007.4441654.

[65] Hou-Sheng Huang. “Efficient hybrid distributed genetic algorithms for wind turbine positioning in large wind farms”. In: *2009 IEEE International Symposium on Industrial Electronics*. 2009, pp. 2196–2201. DOI: 10.1109/ISIE.2009.5213603.

[66] IEA. *Offshore Wind Outlook 2019*. 2019. URL: https://www.iea.org/reports/offshore-wind-outlook-2019.

[67] *Inter-array cable*. URL: https://www.nordseeone.com/engineering-construction/inter-array-cable.html (visited on 03/08/2023).

[68] International Energy Agency. *CO2 emissions in 2022*. https://www.iea.org/reports/co2-emissions-in-2022. Accessed: 2023-11-06. 2022.

[69] International Energy Agency. *Renewables 2021*. https://www.iea.org/reports/renewables-2021. Accessed: 2023-11-06. 2021.

[70] AM Jenkins, M Scutariu, and KS Smith. "Offshore wind farm inter-array cable layout". In: *2013 IEEE Grenoble Conference*. IEEE. 2013, pp. 1–6.

[71] Rongsen Jin et al. "Cable routing optimization for offshore wind power plants via wind scenarios considering power loss cost model". In: *Applied Energy* 254 (2019), p. 113719. ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2019.113719. URL: https://www.sciencedirect.com/science/article/pii/S0306261919314060.

[72] George Katsouris. "Infield cable topology optimization of offshore wind farms". 2015.

[73] Soo Hyun Kim et al. "A study of the wake effects on the wind characteristics and fatigue loads for the turbines in a wind farm". In: *Renewable Energy* 74 (Feb. 2015), pp. 536–543. ISSN: 0960-1481. DOI: 10.1016/J.RENENE.2014.08.054.

[74] Arne Klein and Dag Haugland. "Obstacle-aware optimization of offshore wind farm cable layouts". In: *Annals of Operations Research* 272.1-2 (2019), pp. 373–388.

[75] Bart Hawkins Kreps. "The Rising Costs of Fossil-Fuel Extraction: An Energy Crisis That Will Not Go Away". In: *The American Journal of Economics and Sociology* 79.3 (2020), pp. 695–717. DOI: https://doi.org/10.1111/ajes.12336. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/ajes.12336. URL: https://onlinelibrary.wiley.com/doi/abs/10.1111/ajes.12336.

[76] Andrew Kusiak and Zhe Song. "Design of wind farm layout for maximum wind energy capture". In: *Renewable Energy* 35.3 (2010), pp. 685–694. ISSN: 0960-1481. DOI: https://doi.org/10.1016/j.renene.2009.08.019. URL: https://www.sciencedirect.com/science/article/pii/S0960148109003796.

[77] M. Paul van der Laan et al. "Challenges in simulating coastal effects on an offshore wind farm". In: *Journal of Physics: Conference Series* 854 (May 2017), p. 012046. DOI: 10.1088/1742-6596/854/1/012046.

[78] Markus Lerch, Mikel De-Prada-Gil, and Climent Molins. "A metaheuristic optimization model for the inter-array layout planning of floating offshore wind farms". In: *International Journal of Electrical Power & Energy Systems* 131 (Oct. 2021), p. 107128. ISSN: 0142-0615. DOI: 10.1016/J.IJEPES.2021.107128.

[79] Feng Liu et al. "Wind farm macro-siting optimization with insightful bi-criteria identification and relocation mechanism in genetic algorithm". In: *Energy Conversion and Management* 217 (2020), p. 112964. ISSN: 0196-8904. DOI: https://doi.org/10.1016/j.enconman.2020.112964. URL: https://www.sciencedirect.com/science/article/pii/S0196890420305021.

[80] Clyde & Co LLP. *Opportunities and challenges in Floating Offshore Wind*. Jan. 2022. URL: https://www.clydeco.com/en/insights/2022/01/opportunities-and-challenges-in-floating-offshore.

[81] J. K. Lundquist et al. "Costs and consequences of wind turbine wake effects arising from uncoordinated wind energy development". In: *Nature Energy 2018 4:1* 4 (1 Nov. 2018), pp. 26–34. ISSN: 2058-7546. DOI: 10.1038/s41560-018-0281-2. URL: https://www.nature.com/articles/s41560-018-0281-2.

[82] Grigorios Marmidis, Stavros Lazarou, and Eleftheria Pyrgioti. "Optimal placement of wind turbines in a wind park using Monte Carlo simulation". In: *Renewable Energy* 33.7 (2008), pp. 1455–1460. ISSN: 0960-1481. DOI: https://doi.org/10.1016/j.renene.2007.09.004. URL: https://www.sciencedirect.com/science/article/pii/S0960148107002807.

[83] Florinda Martins et al. "Analysis of fossil fuel energy consumption and environmental impacts in European countries". In: *Energies* 12.6 (2019), p. 964.

[84] Seiied Mohsen Masoudi and Mehdi Baneshi. "Layout optimization of a wind farm considering grids of various resolutions, wake effect, and realistic wind speed and wind direction data: A techno-economic assessment". In: *Energy* (2022).

[85] R. McKenna, P. Ostman v.d. Leye, and W. Fichtner. "Key challenges and prospects for large wind turbines". In: *Renewable and Sustainable Energy Reviews* 53 (2016), pp. 1212–1221. ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2015.09.080. URL: https://www.sciencedirect.com/science/article/pii/S1364032115010503.

[86] Xuan Mei and Min Xiong. "Effects of Second-Order Hydrodynamics on the Dynamic Responses and Fatigue Damage of a 15 MW Floating Offshore Wind Turbine". In: *Journal of Marine Science and Engineering* 9.11 (Nov. 2021), p. 1232. ISSN: 2077-1312. DOI: 10.3390/jmse9111232. URL: http://dx.doi.org/10.3390/jmse9111232.

[87] Prateek Mittal, Kedar Kulkarni, and Kishalay Mitra. "A Novel and Efficient Hybrid Optimization Approach for Wind Farm Micro-siting". In: *IFAC-PapersOnLine* 48.8 (2015). 9th IFAC Symposium on Advanced Control of Chemical Processes ADCHEM 2015, pp. 397–402. ISSN: 2405-8963. DOI: https://doi.org/10.1016/j.ifacol.2015.08.214. URL: https://www.sciencedirect.com/science/article/pii/S2405896315010812.

[88] Jana Mittermaier. *Wind energy pioneer Henrik Stiesdal named European Inventor Award 2018 finalist*. Apr. 2018. URL: https://new.epo.org/en/news-events/press-centre/press-release/2018/452080.

[89] G. Mosetti, C. Poloni, and B. Diviacco. "Optimization of wind turbine positioning in large windfarms by means of a genetic algorithm". In: *Journal of Wind Engineering and Industrial Aerodynamics* 51.1 (1994), pp. 105–116. ISSN: 0167-6105. DOI: https://doi.org/10.1016/0167-6105(94)90080-9. URL: https://www.sciencedirect.com/science/article/pii/0167610594900809.

[90] Walt Musial. *Overview of floating offshore wind (text version)*. Feb. 2020. URL: https://www.nrel.gov/news/video/overview-of-floating-offshore-wind-text.html.

[91] Nicolai Gayle Nygaard and Sidse Damgaard Hansen. "Wake effects between two neighbouring wind farms". In: *Journal of Physics: Conference Series*. Vol. 753. 3. IOP Publishing. 2016, p. 032020.

[92] OffshoreWIND.biz. *Wales' First Floating Offshore Wind Farm Gets Marine License*. https://www.offshorewind.biz/2023/02/23/wales-first-floating-offshore-wind-farm-gets-marine-license/. Accessed: 2023-11-06. Feb. 2023.

[93] Ki-Yong Oh et al. "A review of foundations of offshore wind energy convertors: Current status and future perspectives". In: *Renewable and Sustainable Energy Reviews* 88 (2018), pp. 16–36. ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2018.02.005. URL: https://www.sciencedirect.com/science/article/pii/S136403211830025X.

[94] Juan-Andrés Pérez-Rúa and Nicolaos Antonio Cutululis. "A framework for simultaneous design of wind turbines and cable layout in offshore wind". In: *Wind Energy Science* 7.2 (2022), pp. 925–942.

[95] Vasilis Pettas et al. "On the effects of inter-farm interactions at the offshore wind farm Alpha Ventus". In: *Wind Energy Science* 6.6 (2021), pp. 1455–1472.

[96] AC Pillai et al. "Offshore wind farm electrical cable layout optimization". In: *Engineering Optimization* 47.12 (2015), pp. 1689–1708.

[97] David Pisinger. "Upper bounds and exact algorithms for p-dispersion problems". In: *Computers & Operations Research* 33.5 (2006), pp. 1380–1398. ISSN: 0305-0548. DOI: https://doi.org/10.1016/j.cor.2004.09.033. URL: https://www.sciencedirect.com/science/article/pii/S0305054804002552.

[98] Robert Clay Prim. "Shortest connection networks and some generalizations". In: *The Bell System Technical Journal* 36.6 (1957), pp. 1389–1401.

[99] Krishna Raj P. M., Ankith Mohan, and K. G. Srinivasa. "Signed Networks". In: *Practical Social Network Analysis with Python*. Cham: Springer International Publishing, 2018, pp. 109–144. ISBN: 978-3-319-96746-2. DOI: 10.1007/978-3-319-96746-2_7. URL: https://doi.org/10.1007/978-3-319-96746-2_7.

[100] Pierre-Elouan Réthoré et al. "TOPFARM: Multi-fidelity optimization of wind farms". In: *Wind Energy* 17.12 (2014), pp. 1797–1816. DOI: https://doi.org/10.1002/we.1667. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/we.1667. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/we.1667.

[101] Hegazy Rezk et al. "The Application of Water Cycle Optimization Algorithm for Optimal Placement of Wind Turbines in Wind Farms". In: *Energies* 12 (Nov. 2019), p. 4335. DOI: 10.3390/en12224335.

[102] Hannah Ritchie, Max Roser, and Pablo Rosado. "Energy". In: *Our World in Data* (2022). URL: https://ourworldindata.org/energy.

[103] Shahriar Shafiee and Erkan Topal. "When will fossil fuel reserves be diminished?" In: *Energy Policy* 37.1 (2009), pp. 181–189. ISSN: 0301-4215. DOI: https://doi.org/10.1016/j.enpol.2008.08.016. URL: https://www.sciencedirect.com/science/article/pii/S0301421508004126.

[104] Sedat Şişbot et al. "Optimal positioning of wind turbines on Gökçeada using multi-objective genetic algorithm". In: *Wind Energy* 13.4 (2010), pp. 297–306. DOI: https://doi.org/10.1002/we.339. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/we.339. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/we.339.

[105] Brian Snyder and Mark J. Kaiser. "Ecological and economic cost-benefit analysis of offshore wind energy". In: *Renewable Energy* 34.6 (2009), pp. 1567–1578. ISSN: 0960-1481. DOI: https://doi.org/10.1016/j.renene.2008.11.015. URL: https://www.sciencedirect.com/science/article/pii/S0960148108004217.

[106] Tyler Stehly, Philipp Beiter, and Patrick Duffy. *2019 cost of wind energy review*. Tech. rep. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2020.

[107] Haiying Sun and Hongxing Yang. "Study on three wake models' effect on wind energy estimation in Hong Kong". In: *Energy Procedia* 145 (July 2018), pp. 271–276. ISSN: 1876-6102. DOI: 10.1016/J.EGYPRO.2018.04.050.

[108] Ryota Taninoki et al. "Dynamic cable system for floating offshore wind power generation". In: *SEI Technical review* 84.53-58 (2017), p. 146.

[109] Siyu Tao et al. "Joint optimization of wind turbine micrositing and cabling in an offshore wind farm". In: *IEEE Transactions on Smart Grid* 12.1 (2020), pp. 834–844.

[110] *The rise of renewables*. Oct. 2022. URL: https://www.dnv.com/energy-transition-outlook/rise-of-renewables.html.

[111] Sarina D. O. Turner et al. "A new mathematical programming approach to optimize wind farm layouts". In: *Renewable Energy* 63 (2014), pp. 674–680.

[112] *U.S. Energy Information Administration - EIA - independent statistics and analysis*. June 2022. URL: https://www.eia.gov/energyexplained/energy-and-the-environment/where-greenhouse-gases-come-from.php (visited on 03/08/2023).

[113] *U.S. hydropower output varies dramatically from year to year*. Aug. 2011. URL: https://www.eia.gov/todayinenergy/detail.php?id=2650#.

[114] Union of Concerned Scientists. *Environmental Impacts of Hydroelectric Power*. https://www.ucsusa.org/resources/environmental-impacts-hydroelectric-power. Accessed: 2023-11-06.

[115] Van Oord. *Gemini: Maatschappelijke, ecologische en economische spin-off*. https://www.vanoord.com/nl/duurzaamheid/cases/gemini-maatschappelijke-ecologische-en-economische-spin/. Accessed: 2023-11-06.

[116] Xinbao Wang et al. "A review of aerodynamic and wake characteristics of floating offshore wind turbines". In: *Renewable and Sustainable Energy Reviews* 175 (2023), p. 113144. ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2022.113144. URL: https://www.sciencedirect.com/science/article/pii/S1364032122010255.

[117] Xinbao Wang et al. "A review of aerodynamic and wake characteristics of floating offshore wind turbines". In: *Renewable and Sustainable Energy Reviews* 175 (2023), p. 113144.

[118] *Wind energy frequently asked questions (FAQ): EWEA*. URL: https://www.ewea.org/wind-energy-basics/faq/ (visited on 03/08/2023).

[119] Ryan Wiser et al. "Expert elicitation survey predicts 37% to 49% declines in wind energy costs by 2050". In: *Nature Energy* 6.5 (2021), pp. 555–565.

[120] Yan Wu et al. "A design methodology for wind farm layout considering cable routing and economic benefit based on genetic algorithm and GeoSteiner". In: *Renewable Energy* 146 (2020), pp. 687–698.

[121] Yuan-Kang Wu et al. "Optimization of the Wind Turbine Layout and Transmission System Planning for a Large-Scale Offshore WindFarm by AI Technology". In: *IEEE Transactions on Industry Applications* 50.3 (2014), pp. 2071–2080. DOI: 10.1109/TIA.2013.2283219.

[122] Kiyotomo Yagihashi et al. "Dynamic cable installation for Fukushima floating offshore wind farm demonstration project". In: *Proceeding Jicable*. 2015.

[123] Xiao Yi, Mircea Scutariu, and Kenneth Smith. "Optimisation of offshore wind farm inter-array collection system". In: *IET Renewable Power Generation* 13.11 (2019), pp. 1990–1999.

[124] Peng-Yeng Yin and Tai-Yuan Wang. "A GRASP-VNS algorithm for optimal wind-turbine placement in wind farms". In: *Renewable Energy* 48 (2012), pp. 489–498. ISSN: 0960-1481. DOI: https://doi.org/10.1016/j.renene.2012.05.020. URL: https://www.sciencedirect.com/science/article/pii/S096014811200345X.

[125] Wing Yin Kwong et al. "Multi-Objective Wind Farm Layout Optimization Considering Energy Generation and Noise Propagation With NSGA-II". In: *Journal of Mechanical Design* 136.9 (July 2014). 091010. ISSN: 1050-0472. DOI: 10.1115/1.4027847. eprint: https://asmedigitalcollection.asme.org/mechanicaldesign/article-pdf/136/9/091010/6225598/md_136_09_091010.pdf. URL: https://doi.org/10.1115/1.4027847.

[126] Rune Yttervik. "Hywind Scotland–status and plans". In: *EERA DeepWind* (2015).

[127] Peter Yun Zhang et al. "Solving wind farm layout optimization with mixed integer programs and constraint programs". In: *EURO Journal on Computational Optimization* 2 (2014), pp. 195–219.

[128] Tengjun Zuo et al. "Offshore wind farm collector system layout optimization based on self-tracking minimum spanning tree". In: *International Transactions on Electrical Energy Systems* 29.2 (2019), e2729.