
Design Optimization of Multi-Use Components for Floating Offshore Wind Turbine Substructures

*A dissertation submitted in partial fulfillment
of the requirements for the degree of*

Doctor of Engineering (Dr.-Ing.)

at the University of Rostock
Faculty of Mechanical Engineering and Marine Technology
Chair of Wind Energy Technology

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Rostock, 2024

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Submission date: 24/12/2024

Defense date: 08/07/2025

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Abstract

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Victor Benifla

Climate change poses a significant threat to the environment, raising ecological, economic, and social concerns. To address these interconnected challenges, an urgent transition away from conventional energy sources, such as fossil fuels, is essential. In recent years, offshore wind energy has received significant attention, driving the rapid development of the industry. Offshore wind turbines have become a key component of the global energy transition, offering a scalable and effective solution. Among these, floating offshore wind turbines have emerged as a promising innovation, enabling wind energy to be harnessed in deep waters where fixed-bottom foundations are not feasible. However, despite their potential, floating offshore wind turbines face substantial challenges, primarily due to the high costs of manufacturing, installation, and maintenance.

The floating offshore wind industry has matured significantly in recent years, with various substructure design concepts proposed and developed by the wind energy community. Floating foundations are now optimized not only for performance but also for cost-efficiency and critical aspects such as transportation and installation at both system and farm levels. Many platform design concepts share similar structural components that could be adapted and used across different types of floating substructures as multi-use components. This approach has the potential to streamline the manufacturing process and unlock significant cost reductions to further lower the overall cost of floating offshore wind energy.

The main objective of this thesis is to address the topic of floating offshore wind turbine substructure design optimization, focusing particularly on the GICON®-TLP. This platform features a cylindrical buoyancy body adaptable to other floating foundations and serves as a good example of multi-use components and for developing and evaluating an efficient design optimization framework. An overview of the current state-of-the-art in floating offshore wind turbine modeling and design optimization lays the groundwork for the development of the framework presented. Two numerical models are used for analyzing the floating offshore wind energy system and are coupled with an efficient genetic algorithm to minimize the substructure's overall mass while considering defined constraints. The thesis details the underlying theory of the numerical models as well as the optimization process and its implementation. Finally, a case study demonstrates the framework's efficiency and highlights the cost reductions achievable through optimization and the integration of multi-use components. By introducing an efficient design optimization framework and showcasing the benefits of modular, multi-use components, this thesis provides a practical approach to reducing overall costs and enhancing scalability of floating offshore wind energy.

Acknowledgements

Many people have played an important role during my PhD journey and in the years leading up to it. Their love and support have truly meant the world to me. As I have not always been able to thank them in person, I would like to take this opportunity to express my deepest gratitude here. For those primarily interested in the core content of this thesis, you may proceed directly to page [I](#).

Je tiens premièrement à remercier ma famille chérie d'amour que j'aime tant. Merci à mes merveilleux parents et à mes deux magnifiques sœurs pour votre amour inconditionnel. J'ai une chance incroyable de vous avoir merci pour tout. Merci aussi aux petits derniers : ma nièce Rose et mes petits neveux Jules et Marius. Merci les petits mioches, de me faire rire et de me remplir de bonheur chaque fois que je suis avec vous. Un grand merci également à mes deux bros, Yaya et Quentin, avec qui j'ai l'immense plaisir de partager ma chère famille. Je souhaite aussi remercier tous les membres de la grande tribu Benifla-Missirliu. Je pense à mes grands-parents, mes oncles et tantes chéris, et surtout à tous mes nombreux cousins que j'adore. Merci tout particulièrement à ma cousine adorée Ana, qui m'a toujours accueilli comme un roi et m'a permis de vivre une vraie vie de Berliner. Merci à ma marraine Cath et mon parrain Philippe, ainsi qu'à leurs familles, les Dulac et Bertoncini, et bien sûr, merci à tous les voisins de la rue Desportes. Merci à vous tous avec qui j'ai partagé d'immenses moments de joie et de bonne humeur, qui m'ont toujours fait un bien fou. Vraiment, je ne pourrai jamais exprimer à quel point je suis heureux et chanceux d'avoir une famille aussi formidable. Merci pour tout, et je vous aime tous très fort !

Évidemment, je veux remercier ma magnifique Clara, qui m'accompagne depuis ces dernières années. Merci pour ton amour et ton soutien au quotidien, mais aussi pour m'avoir poussé jusqu'au bout de cette foutue thèse. J'ai hâte de pouvoir enfin consacrer tout mon temps à profiter de la vie avec toi, t'aimer, te faire rire, et, bien sûr, continuer à t'énerver encore plus. Love you, my love! Un grand merci aussi à la petite famille Dubuche, mes ch'tis favoris, qui ont suivi de près mes aventures en Allemagne.

As if I weren't lucky enough, life blessed me with other wonderful and crazy families. I would like to thank the Orzechowskis, whom I love and miss so much. Many years have passed since you welcomed me as a young teenager into your home and treated me like your son. I am incredibly grateful for everything you have brought me and I feel so fortunate to have you as my family. Mr. and Mrs. O, Alex, and Reanna, you will always hold a very special place in my heart, and I look forward to creating many more memories with you all around the world! También quiero agradecer a la familia Cano Villareal, mi familia mexicana, que me recibió por un tiempo corto pero me hizo sentir como en casa, como parte de la familia. Adriana, Armando, Jorge, Alonso, Mariana muchísimas gracias por los momentos tan bonitos que compartimos. Tienen un lugar muy especial en mi corazón y en el de mi familia. ¡Los quiero y los extraño muchísimo!

Je tiens évidemment à remercier tous mes amis, ceux de toujours, mais aussi ceux que j'ai rencontrés plus récemment. Tout d'abord, merci à mes frérots : J.N., Hatem, Robin, Matysse, Loris, Jordan, Adrien et Diku. On se connaît depuis si longtemps, et vous n'imaginez pas à quel point vous m'avez apporté et fait du bien jusqu'à aujourd'hui. Je tiens à remercier mes frérots Michel, Thomas, François, Hugo, Nicolas et Antoine avec qui j'ai partagé mes plus belles années de prépa. Je veux également remercier mes frérots de Bordeaux : Victor, Alexandre B., Alessandro, Paul, Adrien, Ilyes, Vincent et Alexandre L., avec qui j'ai pu découvrir cette belle ville du sud-ouest et même voyager jusqu'au Canada. Merci à vous tous avec ma famille, vous êtes ce que j'ai de plus cher au monde. À chaque fois que l'on a l'occasion de se revoir, c'est une immense joie et beaucoup d'émotion qui me remplit. Merci pour tout, car sans vous tous, c'est pas la meme !

I am deeply grateful to the entire Floating Offshore Wind Energy Network. A special thanks goes to my fellow early-stage researchers, with whom I have shared these incredible past few years. Each of you has had a positive impact on me, making this long PhD journey so much more enjoyable. It would not have been the same without all of you, and I wouldn't have wanted to do it with anyone else. A mi tica favorita, Mariana, mil gracias por ser tan pura vida y por siempre alegrar al grupo. ¡Fue un placer compartir esta aventura con vos! 승윤 형, 지난 몇 년 동안 함께한 즐거운 순간들과 형의 노력에 정말 감사해요! 이제는 PS5로 인생을 즐길 시간이네요! Aan mijn lange en gekke Nederlander, Wessel, Bedankt dat je zo vriendelijk en relaxed bent! Je brengt altijd je serieuzeheid mee naar het werk, en de goede vibes naar het feestje. به نوید، ایرلندی - ایرانی دیوانه، خیلی ممنوم که همیشه اینقدر مهربونی و انرژی مثبت و دیوونگیات رو با همه به اشتراک می‌ذاری! Kutay Patron, dostum, bize getirdiğin tüm nezaket ve pozitif enerji için çok teşekkür ederim! À mon poto Telem, la terreur des buffets, merci pour tout ! On s'est vraiment bien marrés, et sans toi, ça n'aurait pas eu la même saveur. An meinen deutschen Kumpel Moritz, den Segler. Mann, ich werde diesen Hotdog in Porto nie vergessen. Vielen Dank, dass du einfach du selbst bist. Ich wünsche dir immer guten Wind für dein Boot! 晓明, 谢谢你带来的快乐, 以及我们和 '法国狗' 在罗斯托克一起创造的疯狂回忆, 期待有一天能在北京和你一起吃北京烤鸭 À mon gars Dan, l'ours du Canada qui n'a jamais froid ! Merci pour tous ces merveilleux moments passés ensemble et pour tes danses si uniques et inoubliables ! To my bro Craiginho, the most Portuguese of my English lads ! Thank you for being yourself, for all your support, and for all the amazing times we shared in Lisboa ! Last but not least, je veux remercier mon frère Thomas, sans qui rien n'aurait été possible ! Merci d'être toi-même, de m'avoir aidé et soutenu ces dernières années, et pour tous ces moments inoubliables. Bien sûr, impossible d'oublier Florent, tout simplement le GOAT des project managers ! Merci d'avoir toujours été là pour nous, et ce fut un immense plaisir de partager ces dernières années avec toi.

Ich möchte allen Menschen danken, die ich in der schönen Stadt Rostock kennengelernt habe, sowie allen, die ich während meiner Zeit in der wunderbaren Stadt Berlin getroffen habe. Dort habe ich wirklich tolle Leute getroffen, die einen großen Unterschied in meinem Leben gemacht haben. Ich bin euch allen sehr dankbar, und ihr werdet immer einen besonderen Platz in meinem Herzen haben. An meinen lieben Mitbewohner

Kayoway und meine Fußballfreunde Rasmus, Moritz und Pascal: Vielen Dank, dass ihr das Leben in Rostock so unvergesslich gemacht habt. Ich bin wirklich dankbar für die Zeit mit euch! Danke auch an meine Kollegen und Freunde am Lehrstuhl für Windenergietechnik: Jessica, Fatma, Hauke, Daniel, Paul S., Paul N. Habib, Qian, Mohsen und Robert. Eure Hilfe und gute Laune haben meine Zeit an der Universität viel einfacher und schöner gemacht. También quiero agradecer a mi querido amigo español Ignacio, a quien conocí en la clase de alemán. Compartimos las mismas dificultades de hacer un doctorado en el extranjero, y fue realmente agradable tenerte a mi lado. Je tiens également à remercier mon ami Julien, avec qui j'ai partagé cette idée un peu folle de faire un doctorat en Allemagne.

Finally, I want to thank my supervisors at the University of Rostock, Frank Adam and Uwe Ritschel. Thank you for kindly hosting me at the beginning of the project and for giving me this incredible opportunity to pursue my education in an environment I couldn't have wished for better. I am also grateful to the teams at GICON and particularly the team at WavEC for hosting me during my secondments and providing me with invaluable support and a lot of fun!

...Tchimbé rèd pa moli ...Sé moli a ki rèd !

– JnKong

Contents

List of Figures	III
List of Tables	V
List of Acronyms	VII
1. Introduction	1
1.1. Offshore Wind Energy	2
1.2. Floating Offshore Wind Potential in Europe	7
1.3. The Floating Offshore Wind Energy Network	14
1.4. Objective and Outline	15
2. State-of-the-Art	17
2.1. Floating Offshore Wind Turbine Substructure	17
2.1.1. Classification	17
2.1.2. Design process	21
2.1.3. Design trends	23
2.2. Floating Offshore Wind Turbine Modeling	25
2.2.1. Aerodynamics	26
2.2.2. Hydrodynamics	27
2.2.3. Mooring analysis	29
2.2.4. Structural analysis	30
2.2.5. Numerical tools	30
2.3. Design Optimization of Floating Offshore Wind Turbine Substructure . .	32
2.3.1. Literature review	33
2.3.2. Genetic algorithms	34
3. Development of an Efficient Design Optimization Framework	37
3.1. Objective	37
3.2. The GICON®-TLP	38
3.3. The Universal Buoyancy Body	40
3.4. Numerical Models	42
3.4.1. Structural model	43
3.4.2. Dynamic model	44
3.5. Optimization Process	49
3.6. Implementation	57
3.7. Validation	59

4. Design Optimization of the GICON®-TLP	63
4.1. Design Approach	63
4.2. Structural Optimization of the Universal Buoyancy Body	64
4.2.1. Design Parametrization	64
4.2.2. Problem formulation	65
4.2.3. Results	67
4.3. Dynamic Optimization of the GICON®-TLP	69
4.3.1. Design parametrization	69
4.3.2. Problem formulation	71
4.3.3. Results	74
4.4. Discussions	76
5. Conclusion	79
5.1. Outlooks	81
Appendix	83
A. Additional Metocean Data in Europe	83
B. Optimization Test Problems	87
B.1. Problem Definitions	87
B.2. Optimization results	89
Bibliography	91

List of Figures

1.1. Carbon emissions and temperature change	1
1.2. Global warming impact across generations	2
1.3. The first and largest offshore wind farm in the world	3
1.4. The first floating offshore wind farm in the world	4
1.5. Installed capacity of offshore wind energy worldwide	5
1.6. Evolution of the levelized cost of energy for offshore wind	6
1.7. Water depth distribution in Europe	7
1.8. Wind resource distribution in Europe	8
1.9. Wave conditions across Europe	9
1.10. Analysis of water depth and wind speed in Europe	11
1.11. Potential sites for floating offshore wind farm deployment in Europe	13
1.12. The FLOating Wind Energy netwoRk	14
2.1. Substructure classification for floating offshore wind turbines	19
2.2. Examples of installed floating offshore wind turbines	20
2.3. Stability mechanisms in floating offshore wind turbine substructures	21
2.4. The design process for floating offshore wind turbines	22
2.5. Future design concepts for floating offshore wind turbine substructures	23
2.6. Offshore environment and degrees of freedom	25
2.7. Mooring line configurations for floating offshore wind turbines	29
2.8. Numerical models for aerodynamic and hydrodynamic analysis	31
2.9. The general structure of genetic algorithms	35
3.1. Development path of the GICON [®] -TLP	38
3.2. Installation process for the GICON [®] -TLP	39
3.3. Experimental analysis of the GICON [®] -TLP	40
3.4. The Universal Buoyancy Body	41
3.5. Multi-use component integration	42
3.6. Structural model of the Universal Buoyancy body	43
3.7. Member-based modelling of the GICON [®] -TLP	45
3.8. Structure of the genetic algorithm implemented	50
3.9. Sampling methods for initial population generation	51
3.10. Illustration of the fitness scaling operation	53
3.11. Illustration of the crossover and mutation operations	55
3.12. Illustration of the addition operation	56
3.13. Global structure of the design optimization framework	57
3.14. Final population distribution for the Gomez-Levy function	60
3.15. Evolution of the objective and constraints for the welded beam problem	61
3.16. Final population distribution for the welded beam problem	62

4.1.	Design parametrization of the Universal Buoyancy Body	65
4.2.	Optimized design of the Universal Buoyancy Body	68
4.3.	Design parametrization of the GICON [®] -TLP	69
4.4.	Examples of design solution for the GICON [®] -TLP	70
4.5.	Illustration of the dynamic model for the GICON [®] -TLP	72
4.6.	Design load cases considered for analysis	73
4.7.	Objective and constraints evolution for the GICON [®] -TLP problem	75
4.8.	Dynamic performance of the optimized GICON [®] -TLP design	77
4.9.	Final population distribution for the GICON [®] -TLP problem	78
A.1.	Exclusive economic zones and distance to shore in Europe	83
A.2.	Extreme wave conditions in Europe	83

List of Tables

1.1. Definitions of offshore wind farm types	10
1.2. Definitions of wind classes	10
3.1. Materials properties	44
3.2. Hydrodynamic properties of the GICON [®] -TLP	48
3.3. Natural frequencies of the GICON [®] -TLP	59
4.1. Optimization results for the Universal Buoyancy Body problem	67
4.2. Optimized design of the Universal Buoyancy Body	68
4.3. Characteristics of the IEA 15 MW	71
4.4. Mooring lines properties	71
4.5. Optimization results for the GICON [®] -TLP problem	74
4.6. Optimized design of the GICON [®] -TLP	76
4.7. Potential cost reductions	78
A.1. Area covered by offshore wind farm types	84
A.2. Area covered by wind speed classes	85
A.3. Area of potential sites for floating offshore wind farm deployment	86
B.4. Optimization results for the Three-Hump-Camel function	89
B.5. Optimization results for the Schwefel function	89
B.6. Optimization results for the Hartmann Function	89
B.7. Optimization results for the Sphere Function	90
B.8. Optimization results for the Gomez-Levy Function	90
B.9. Optimization results for the welded beam problem	90

List of Acronyms

APDL	Ansys Parametric Design Language
BEM	Blade Element Momentum
CFD	Computational Fluid Dynamics
CMNGA	Cumulative Multi Niching Genetic Algorithm
DLC	Design Load Case
EEZ	Exclusive Economic Zone
EU	European Union
FD	Frequency Domain
FEA	Finite Element Analysis
FLOAVER	FLOAting Wind Energy netwoRk
FLOW	Floating Offshore Wind
FOWT	Floating Offshore Wind Turbine
GA	Genetic Algorithm
GICON	Großmann Ingenieur Consult GmbH
IEA	International Energy Agency
LCoE	Levelized Cost of Energy
LHS	Latin Hypercube Sampling
LWET	Lehrstuhl für Windenergietechnik
MSL	Mean Sea Level
OW	Offshore Wind
OWT	Offshore Wind Turbine
QTF	Quadratic Transfer Function
RAFT	Response Amplitudes of Floating Turbines
RAO	Response Amplitude Operator
RNA	Rotor Nacelle Assembly
SBC	Simulated Binary Crossover
TD	Time Domain
TLP	Tension Leg Platform
UBB	Universal Buoyancy Body
UK	United Kingdom

Introduction

In today's world, climate change poses a major threat to the environment, leading to extreme weather events and disruptions to ecosystems. The unsustainable use of natural resources, such as water, land, and energy, exacerbates this issue and presents long-term challenges that could become irreversible. Additionally, the ongoing global energy crisis highlights the finite nature of our resources and raises ecological, economic, and social concerns. To address these interconnected challenges, an urgent transition away from conventional energy sources, such as fossil fuels, is essential. Recent reports from the scientific community emphasize that greenhouse gas emissions from human activities have accelerated global warming at an unprecedented rate [1, 2]. Figure 1.1 shows the significant rise in the Earth's surface temperature compared to the pre-industrial era, indicating it is likely to reach 1.5°C by the early 2030s, regardless of future emissions scenarios [1]. As illustrated in Figure 1.2, both climatic and non-climatic risks are expected to intensify, posing increasingly complex challenges for future generations.

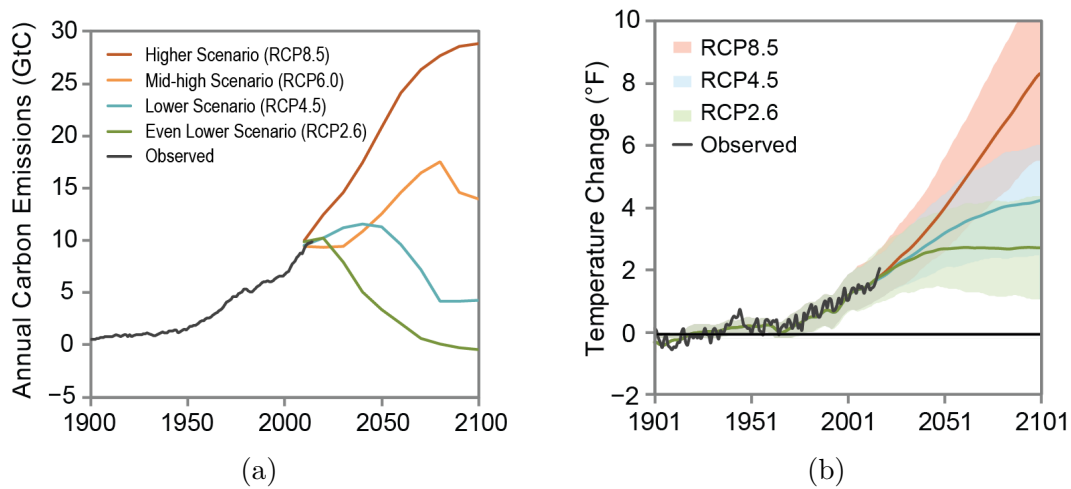


Figure 1.1. Observed and projected future carbon emissions (a) and the resulting temperature change relative to the 1901-1960 average (b), from [2].

Given the urgency to address these challenges and transition away from traditional, emissive energy sources, there has been a surge in the development of renewable energy in recent years. The Paris Agreement stands a strong global commitment to limit global warming to below 2°C above pre-industrial levels [3]. Achieving this objective requires immediate and substantial reductions in emissions, with the goal of reaching net-zero CO_2 emissions. The EU has implemented robust renewable energy directives, raising the target from 32 % to at least 40% of renewable energy in its overall energy mix by 2030 [4, 5].

The United States have officially rejoined the Paris Agreement in early 2020, while China has announced its ambitious plan to peak CO₂ emissions before 2030 and achieve carbon neutrality by 2060 [6]. Recently, the EU unveiled a plan to rapidly reduce its reliance on fossil fuels. Through strategies such as energy conservation, cleaner production, and diversification, the European Commission proposed raising the renewable energy target to a 45% share of the overall energy mix by 2030 [7]. Although this transition may be seen as overdue, it reflects a growing recognition within the international community of the urgent need for sustainable energy alternatives.

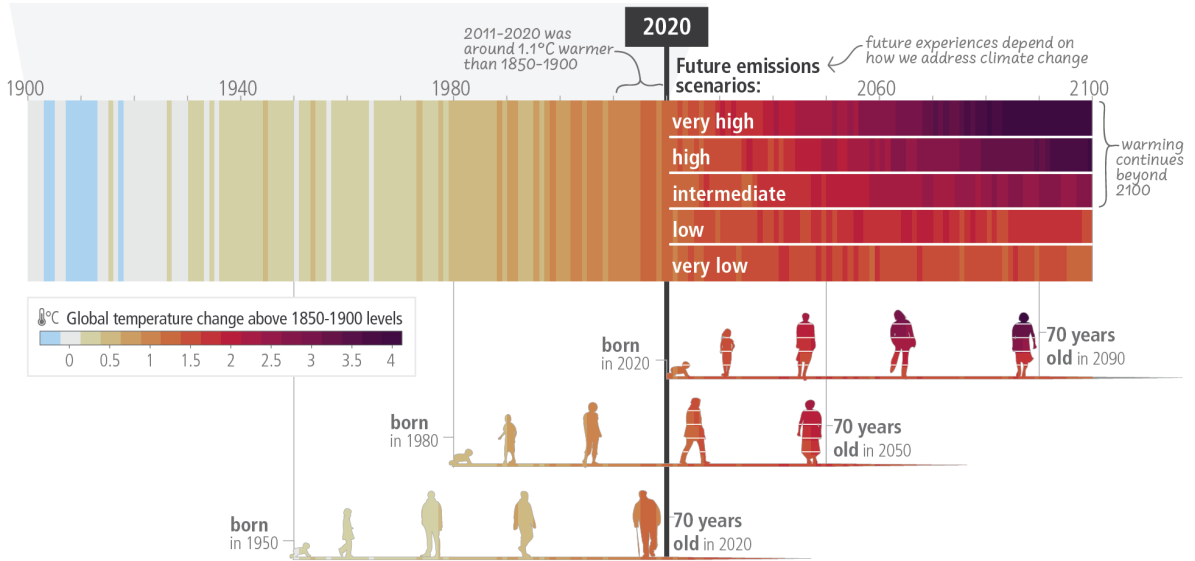


Figure 1.2. Earth's temperature change and its implications for past, present, and future generations, across various future scenarios, from [1].

1.1. Offshore Wind Energy

Among renewable energy sources, wind power is considered one of the most reliable and well-established industries. OW energy involves generating electrical power from wind turbines installed in offshore environments, typically at sea or in the ocean. Offshore technologies offer several advantages over conventional onshore wind energy, such as consistent and strong wind speeds over open water, which allow turbines to generate more electricity. Moreover, wind farms can be located near densely populated coastal areas or far offshore, reducing their impact on local communities while enhancing energy distribution efficiency. Recently, OW energy has received significant attention and gained popularity among renewable energy sources, leading to the rapid development of the sector due to increased interest and efforts from both industry and policymakers. In the current context, OWTs are emerging as a crucial component of the global energy transition, providing a scalable and effective solution to address the pressing challenges mentioned.

The Vindeby wind farm, commissioned in 1991 in Denmark, is generally considered the world's first **OW** project. It consisted of 11 wind turbines, each with a capacity ranging from 400 to 450 kW, resulting in a total capacity of approximately 5 MW [8]. This project marked a significant milestone in the development of **OW** energy and provided valuable insights into the feasibility and challenges of such energy systems. Since then, numerous projects have been developed worldwide, featuring larger and more advanced installations. Currently, the largest operational **OW** project in the world is the Hornsea 2 wind farm, located in the North Sea off the coast of the **UK**. For comparison, Hornsea 2 has a total capacity of 1.32 GW and consists of 165 wind turbines, each with a capacity of 8 MW [9]. Figure 1.3 illustrates this evolution by comparing the turbines' properties, highlighting the progress of this technology and the increasing scale of projects.

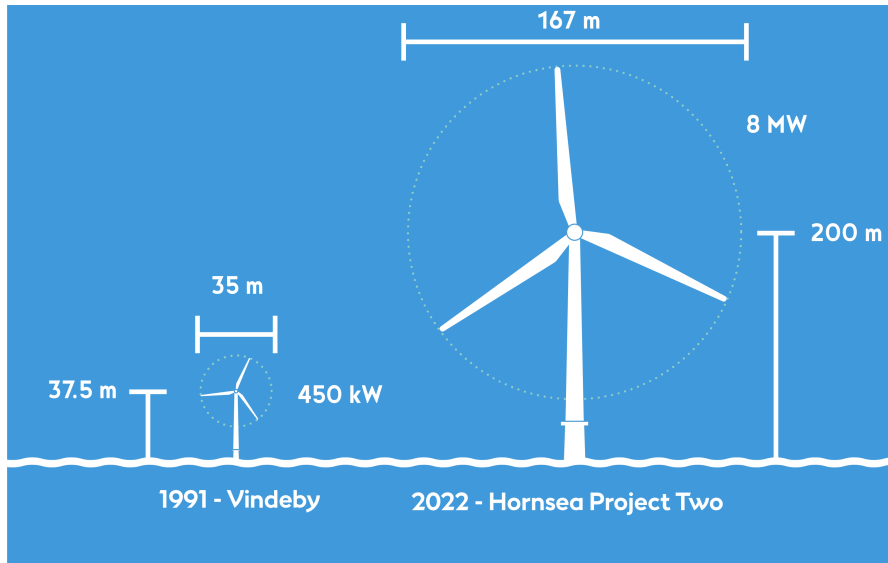


Figure 1.3. Illustration of the main characteristics of the first (Vindeby) and largest (Hornsea 2) **OW** farm in the world, adapted from [9].

The global potential for deploying **OWTs** is vast, yet a significant portion remains untapped due to technical and cost-related challenges. Traditional bottom-fixed **OWTs** are limited in deep waters, where installation becomes excessively complex and costly [10]. To overcome these limitations, **FOWTs** have emerged as a promising alternative, allowing wind energy to be harnessed in areas where fixed-bottom foundations are impractical. These floating substructures enable turbines to be installed in deep waters with minimal seabed impact and can be easily removed for decommissioning or maintenance [11]. **FOW** energy presents opportunities for significant cost savings throughout the entire lifecycle of the wind energy system, as components can be fabricated and assembled onshore and towed offshore. Additionally, deeper offshore waters often provide better wind conditions, which enhance energy production and reduce costs. This technology expands the scope of **OW** energy, offering a viable solution to access wind resources in a variety of challenging offshore environments.

The world's first **FOWT** is known as Hywind Demo, a 2.3 MW full-scale prototype installed off the coast of Norway in 2009. The turbine is supported by a long, cylindrical, and heavily ballasted floating substructure moored to the seabed. This project demonstrated the feasibility and performance of this particular technology, leading to the commissioning of the first commercial-scale wind farm, Hywind Scotland, in 2017. The wind farm consists of 5 **FOWTs**, shown in Figure 1.4, installed at water depths averaging 100 m and with a total capacity of 30 MW [12]. Currently, the largest operational **FOW** project in the world is the Hywind Tampen wind farm, which uses the same floating technology as the previous Hywind projects. Fully operational since 2023, the wind farm is located off the west coast of Norway, with water depths up to 300 m and features 11 turbines with a total installed capacity of 88 MW [13]. Several other projects have been initiated in different parts of the world, contributing to the technical development of the industry and the growth of the market.



Figure 1.4. Hywind Scotland, the first **FOW** farm in the world, from [12].

In recent decades, the entire **OW** industry has grown tremendously in terms of technology and commercial development, as shown by many market status reports [14–16]. Figure 1.5 provides the latest data on the worldwide installed capacity, highlighting the two leading players in the industry. In 2018, Europe accounted for over 80% of this capacity, with wind farms predominantly located in the North Sea off the coast of the **UK** [17]. Currently, Europe and China contribute to nearly all operational capacity worldwide, each surpassing 30 GW [14], resulting in a total capacity of 63.2 GW [15]. Additionally, new projects are emerging globally, particularly in Asia (Japan, South Korea, and Vietnam) and in the United States, where wind farms and prototypes are expected to become operational in the coming years [14, 16]. The expansion of the **OW** market is projected to continue, with an increase of over 380 GW anticipated in the next decade [14], underscoring the economic viability of this renewable energy source, which continues to attract significant investments and initiatives. This growth also underscores the critical role of this particular resource in meeting global energy demands and achieving renewable energy targets.

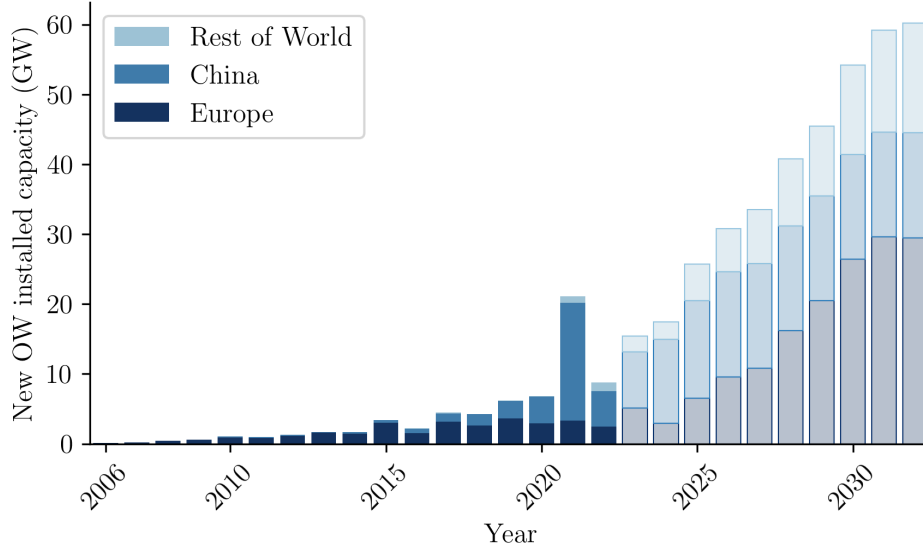


Figure 1.5. Observed (solid) and expected (shaded) new additions of **OW** (fixed and floating) installed capacity worldwide, adapted from [14].”

Due to the different technical advancements, the growing number of projects developed, and the growth of the market, the cost of this energy has quite surprisingly decreased over the years. The **LCoE** serves as a standard measure for comparing energy expenses from different sources, including renewable energies. It represents the average cost of generating one unit of a given energy source and is computed as the ratio of the total system cost to the overall energy produced [18]. Recently, there has been a significant reduction in the **LCoE** of **OW** energy, as shown in Figure 1.6, which provides cost data from installed and expected future projects, gathered and analyzed in [19]. In general, projections show that this energy is likely to become more affordable in the future, enhancing its competitiveness with other renewable and conventional energy sources. Although the installation costs for **OW** projects remain higher compared to onshore wind, they tend to produce more energy, which could result in lower total costs [19]. Over the past decade (2010-2022), the global weighted average **LCoE** for **OW** energy has significantly decreased from nearly $\$0.2 \text{ kWh}^{-1}$ to $\$0.08 \text{ kWh}^{-1}$ [18].

This cost reduction is mainly due to technical improvements that enable the use of more efficient **OWTs** and the deployment of larger wind farms. Modern projects benefit from past developments and feature larger, more powerful structures, as well as streamlined fabrication and installation processes. Additionally, the expanding market attracts more investors who are increasingly comfortable and experienced with developing such projects. Forecasts indicate that by 2050, the mid-range **LCoE** value is expected to be around $\$0.05 \text{ kWh}^{-1}$, and this could be achievable for certain projects as early as 2030 [19]. Similar trends are observed with **FOW** energy as the industry matures and enters the commercial stage. Currently, the total number of floating turbines installed and operational is limited, with less than 200 MW [14].

While floating technologies remain more expensive than bottom-fixed turbines, ongoing technological advancements are expected to reduce these costs. The LCoE of FOW projects currently stands at less than $\$0.22 \text{ kWh}^{-1}$ [19] and is expected to further decrease in the future. By 2050, the average value is estimated to be around $\$0.06 \text{ kWh}^{-1}$, slightly higher than the expectations for bottom-fixed OW energy [20]. This drop is anticipated to occur even faster, as FOW energy is now 50 % cheaper than predicted a few years ago [21].

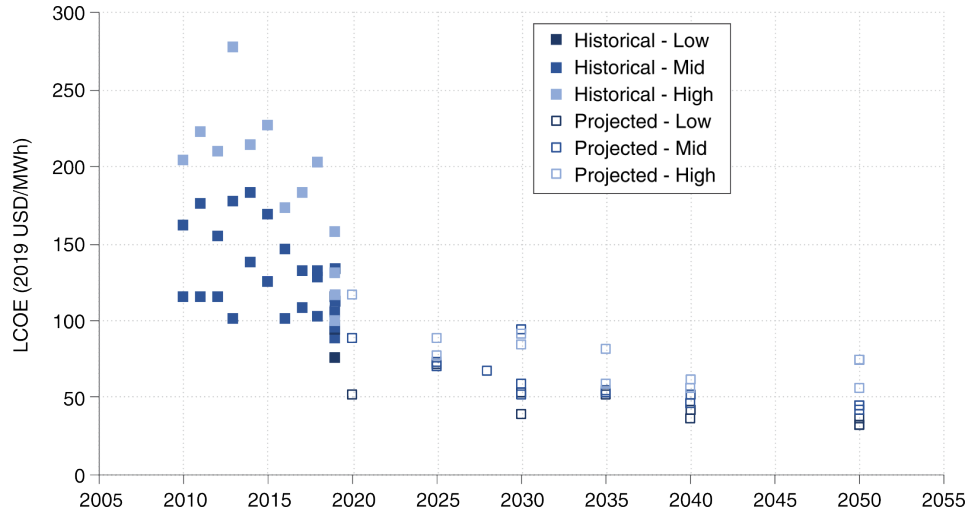


Figure 1.6. Historical and projected ranges of LCoE values for OW projects, from [19].

Although the OW industry has experienced significant developments and become increasingly cost-effective, it is essential to recognize and explore the existing limitations of this renewable energy. The required investments for developing such projects remain considerable compared to other energy sources. Producing, installing, and repairing OWTs can be challenging and costly due to their remote locations, which require specialized vessels, equipment, and infrastructure. While the LCoE is anticipated to decrease, substantial research and development efforts are still needed, particularly for FOW energy, to achieve the significant cost reductions mentioned. Additionally, the current energy crisis and potential future economic disruptions may affect the supply chain and market dynamics. Major oil and gas companies have positioned themselves as leaders in renewable energy, particularly in OW. However, some have announced plans to scale back or exit projects due to unmet profit expectations [22]. This uncertainty could hinder further development of the industry, highlighting the importance of diversifying energy sources rather than focusing all efforts on a single solution. While OW undeniably offers a promising way to address climate change and reduce human-related emissions, it will require time, and the most immediate way to cut emissions is to avoid producing them. Furthermore, despite its environmental benefits, it can still have significant environmental impacts, such as potential disruptions to marine ecosystems and wildlife [23, 24]. It is crucial to consider and address these environmental consequences to ensure a sustainable and responsible transition to OW energy for the future.

1.2. Floating Offshore Wind Potential in Europe

The installed capacity of **OW** energy in the **EU** is expected to reach 300 GW in 2050 by deploying both bottom-fixed and floating turbines [5]. Most maritime areas in Europe have water depths greater than 60 m, except in the southern North and Baltic Sea, as seen in Figure 1.7 which shows the water depth within the **EEZ** of different countries in Europe and their detailed delimitations are given in appendix, see Section A. In deep water, floating foundations are the most cost-effective and often the only feasible solution [10]. A maritime area may be suitable for the deployment of **FOW** farms, depending on water depth, metocean conditions, distance to shore and ports, soil types, and various other constraints. Accessing and analyzing these data can often pose challenges due to their limited availability or complex nature.

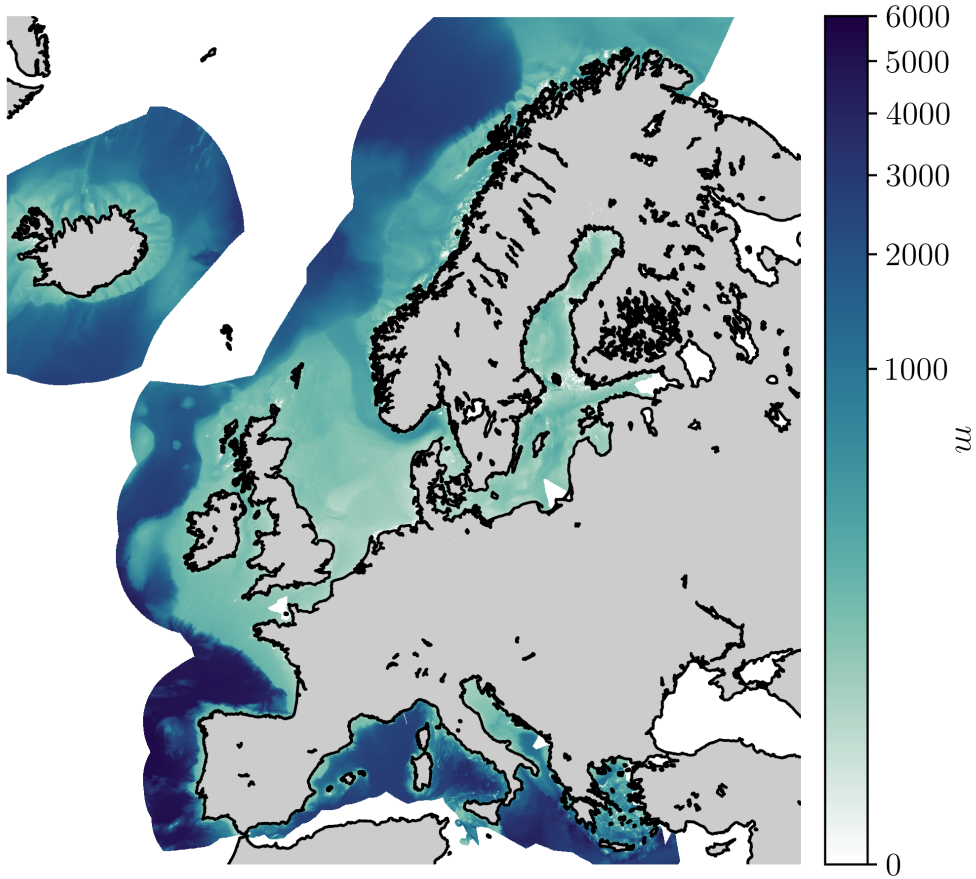


Figure 1.7. Water depth within the **EEZ** of different countries in Europe.

As a significant development, the Copernicus program released global climate and weather data in 2018, known as the ERA5 dataset [25]. ERA5 data, joins model-generated data with observations from various parts of the world to create a globally comprehensive and coherent dataset. It offers valuable insights into wind and wave characteristics worldwide and has undergone rigorous validation in numerous studies.

In addition to this dataset, to assess the FOW potential of the different European seas and oceans, the following open source data is collected, processed and analyzed:

- Hourly mean wind speed at 100 m height above sea level, from [25]
- Hourly mean significant wave height and peak period, from [25]
- Water depth, from [26]
- EEZs, from [27]
- Distance to the closest shore (computed)

In this analysis, 10 years of data (2011-2020) is used in order to assess the wind resource and 20 years of data (2002 - 2021) for evaluating the wave conditions. These selected time periods strike a balance between gathering sufficient data to derive meaningful statistics while ensuring reasonable computational efficiency. From the 10 years of wind speed data, the mean wind speed at 100 m height and the wind availability are computed. This height corresponds to the hub height of current OWTs, for which the rated power of a single turbine is around 10 MW. The wind resource might be better at heights greater than 100 m, however the overall conclusions when comparing different regions are expected to be similar. The availability, for a given wind speed range, is defined as the number of hours per year for which the wind has a velocity within the considered range. This parameter is used in [28] to quantify the wind resource in the Atlantic. Here, a wind speed range of $11 \text{ m} \cdot \text{s}^{-1}$ to $25 \text{ m} \cdot \text{s}^{-1}$ is considered, which represents the range from the rated to cut-out wind speed for a typical multi-MW wind turbine. The wind resource in Europe is shown in Figure 1.8.

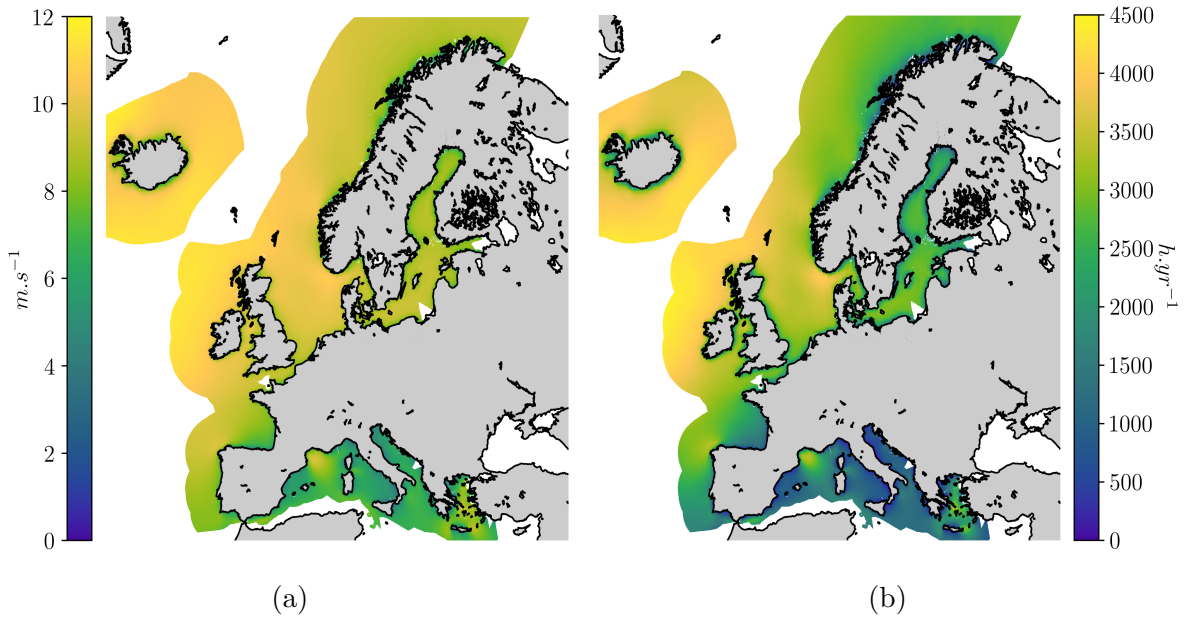


Figure 1.8. Mean wind speed (a) and availability (b) in Europe.

Wave data is post-processed to determine the mean significant wave height and peak period which are shown in Figure 1.9. In addition, extreme waves are considered by computing the significant wave heights with return period of 1 and 20 years and are shown in appendix, see Figure A.2. The distribution of significant wave heights is assumed to follow a 2-parameter Weibull distribution, as outlined in the standard [29]. For each grid point in the ERA5 data, the wave height distribution over a given number of years is determined using 0.5 m bins. Wind resources are strongest in northern Europe, especially in the seas around Ireland, the UK, Iceland, and Norway, where mean speeds exceed $10 \text{ m} \cdot \text{s}^{-1}$ and availability reaches $4500 \text{ h} \cdot \text{yr}^{-1}$. Other good regions include the Atlantic near northern Portugal, western Spain, and Brittany, France. The Gulf of Lion in the northern Mediterranean also has a strong wind resource, while the rest of the Mediterranean has relatively lower wind potential, except for certain areas in Greece.

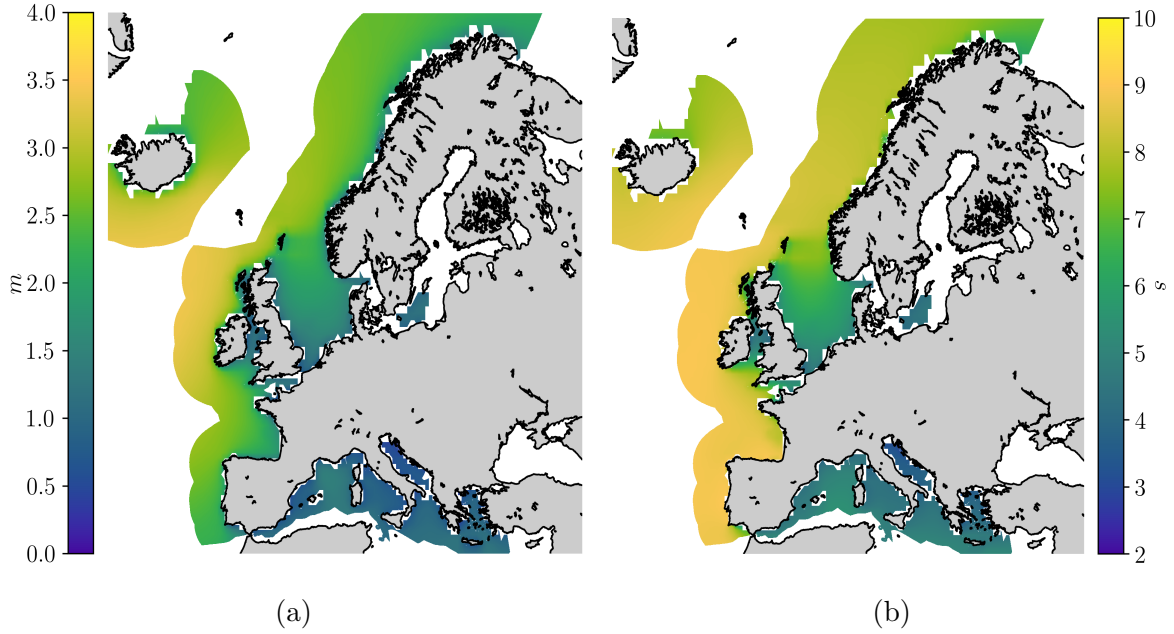


Figure 1.9. Mean significant wave height (a) and peak period (b) in Europe.

Wave conditions are milder in the Mediterranean Sea, with mean wave heights below 1.5 m, compared to the Norwegian Sea and the Atlantic, where they can reach up to 4.0 m. The waves are also relatively shorter there, with about a 5 s difference in the mean values of the wave peak period. The extreme significant wave height shown in appendix, see Section A, is about 50 % higher in the Atlantic and the North of Europe compared to the Mediterranean sea, except for some area between Sardinia and Spain, values can be as high as 14.5 m, which needs to be taken into account when designing FOWT for such sites. The lowest wind resource in the Mediterranean is balanced by its milder wave conditions offering an environment for which smaller substructures might be beneficial. An interesting region lies between Scotland and Norway, where the wind resources are excellent and the waves are not too extreme, making it an excellent region for FOW farm deployment.

The first generation of floating wind farms will be installed in areas with high wind resources, intermediate water depths and close to shore and to potential docks and construction sites. For low water depths, below 60 m, fixed foundations are the most cost-effective solution for the deployment of **OW**. For water depths between 60 and 100 m, floating foundations, jackets or other types of fixed foundations may be suitable for **OWTs** substructures, making them hybrid farms. A lot of the **OW** farms foreseen in the coming years (2025-2030) will be installed in areas with such water depths. The areas where the water depths is between 100 and 350 m are referred to as 1st gen., because several floating wind farm projects under development (**UK**, Norway, Spain, France, etc [14]) are located in such range of water depths, thus being part of the first generation of floating wind farms. The second generation of **FOW** farms (2nd gen.) is defined for water depths between 350 and 1000 m, for which installation is more complex than for lower depths but will still be achieved in the near future. Finally, **FOW** farms deployed in deep water depths over 1000 m will be installed in the far future, mainly due to technical constraints which are much more challenging for now. Table 1.1 depicts the different water depths ranges for the **OW** farm types defined here.

Table 1.1. Definitions of **OW** farm types based on water depth.

Type	Fixed OW	Hybrid OW	1 st gen. FOW	2 nd gen. FOW	Future gen. FOW
Water depth (in m)	[0, 60)	[60, 100]	(100, 350]	(350, 1000]	> 1000

Similarly, table 1.2 depicts the different wind classes defined for the analysis and are related to the mean wind speed. They are based on the commonly used wind classes defined in [30] and often used in the literature. It represents the range of mean wind speed at hub height, covering very low wind (class IV) to high wind (class I⁺).

Table 1.2. Definitions of wind classes based on mean wind speed.

Class	IV	III	II	I	I ⁺
Mean wind speed (in $\text{m} \cdot \text{s}^{-1}$)	< 6	[6, 7.5]	(7.5, 8.5]	(8.5, 10]	> 10

Figure 1.10 shows the repartition in Europe of the **OW** farm types and wind classes defined for this analysis. In addition, the details of the area covered by each type and class for each country are given in appendix, see Section A. In Figure 1.10a, the zones with water depth inferior to 60 m are logically located very close to the coast for most countries.

The only exceptions are the southern part of the North Sea and the Baltic Sea with relatively shallow waters, where most of the fixed **OW** farms installed in Europe are located. Finland, Germany, Poland, Sweden, Denmark, Latvia, Lithuania, Belgium and the Netherlands have more than 50 %, for some even more than 70% of their seas at depths less than 60 m. The areas where hybrid **OW** farms could be installed are mainly located in the northwest and southeast of the **UK** and in the Baltic Sea. The second most covered area is the one where potential 1st gen. **FOW** farms could be installed, with about $1050 \times 10^3 \text{ km}^2$ of area covered in Europe. In these areas, only floating foundations are suitable for installation. It covers a large part of western France and Ireland, northern **UK**, Norway and Iceland, as well as some areas in the seas of Spain, aligning with future announced **FOW** projects [14]. Deeper regions are further from the coast, mainly in the Atlantic, Irish, Italian and Albanian seas, as well as in Norway, the **UK** and Iceland. Most of the **EEZs** in Europe are in water depths greater than 1000 m. Much of the Mediterranean, the Atlantic and the northern part of the North Sea is in very deep waters. Countries such as Spain, Portugal, Italy, Greece, Iceland, France and Ireland have a significant area of their **EEZ** in deep water. This limits the possibility of installing **FOWTs** in these areas, at least in the near future, as floating technologies still face technical challenges for those depths. Regarding the wind classes, in Figure 1.10b, from the Atlantic to the whole of northern Europe, the average wind speed is above $8.5 \text{ m} \cdot \text{s}^{-1}$ almost everywhere, with high resource regions in the **UK**, Ireland, Norway and Iceland. In comparison, the Mediterranean is less windy, with average winds below $7.5 \text{ m} \cdot \text{s}^{-1}$, making it less advantageous for wind energy.

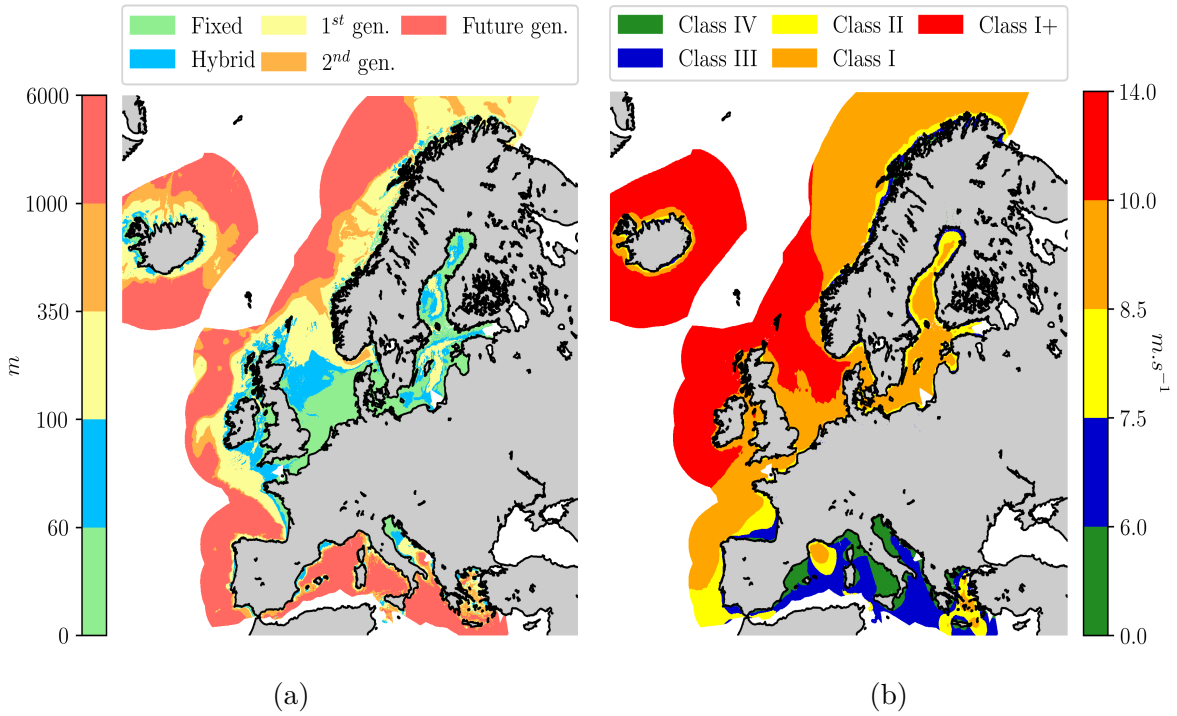


Figure 1.10. Repartition of the **OW** farm types (a) and wind classes (b) defined.

When evaluating potential locations for FOW farms, several criteria must be considered. It is imperative that potential deployment sites exhibit important wind availability to qualify as viable options. The distance from shore is another key factor to take into account and is shown in appendix, see Section A. A balance is needed as a wind farm should be located far enough from the coast to minimize visual impact but also close enough to prevent excessive costs, such as those incurred during installation and for the export cable. It's also important to identify areas prone to severe sea states, as harsh conditions can increase the cost of substructure design. Based on this analysis, potential FOW development sites are assessed, and countries with the greatest energy potential are identified. This process involves evaluating each country's EEZ based on the following criteria:

- Adequate water depths, ranging from 60 to 1000 m
- Optimal proximity to the shore, falling within a range of 10 to 150 km
- Strong mean wind speeds exceeding $7.5 \text{ m} \cdot \text{s}^{-1}$
- Important availability exceeding $2000 \text{ h} \cdot \text{yr}^{-1}$

In Figure 1.11, the specific regions that fulfill these criteria can be observed. In addition, the details of the area covered by each country respecting these criteria are given in appendix, see Section A. Remarkably, Iceland, Norway, and the UK stand out with the largest expanses, covering 178 , 300 , and $314 \times 10^3 \text{ km}^2$ of suitable area, respectively. The UK possesses a distinct advantage, as the majority of its area lies at depths of less than 200 m, making it exceptionally conducive for FOW installations. In contrast, Iceland and Norway exhibit greater water depths, though still averaging less than 400 m. These three nations share a similar distribution of distance to the shore, each with a median distance of about 70 km. Regarding wind resources, both the UK and Iceland have significant areas with more than $3000 \text{ h} \cdot \text{yr}^{-1}$ of availability, while Norway maintains a median availability of the same amount. Sweden, France, and Ireland also show substantial potential for FOW energy, with areas of 68, 83, and $126 \times 10^3 \text{ km}^2$, respectively. The majority of their offshore waters are relatively shallow, with depths of less than 200 m. Sweden holds an advantage in proximity to the coast, as a large portion of its sites are within 70 km of the shore, in contrast to France and Ireland. Ireland has a superior wind resource, with a median wind speed of $10.5 \text{ m} \cdot \text{s}^{-1}$, while Sweden and France maintain similar averages at $9 \text{ m} \cdot \text{s}^{-1}$. This pattern also holds true for wind availability. Other countries such as Greece, Finland, and Spain show significant potential for floating wind energy as well. Water depths in Greece and Spain vary between 60 and 1000 m, while in Finland, depths generally do not exceed 200 m. Greece and Spain also benefit from shorter distances to shore, with most locations within 60 km, unlike Finland. Notably, while Finland offers better wind resources, these countries each present their own advantages and challenges in terms of wind energy development. Lastly, several other countries, including Denmark, Estonia, Latvia, Poland, and Portugal, collectively offer around $10 \times 10^3 \text{ km}^2$ of available area for FOWT, further expanding the potential for this sustainable energy source.

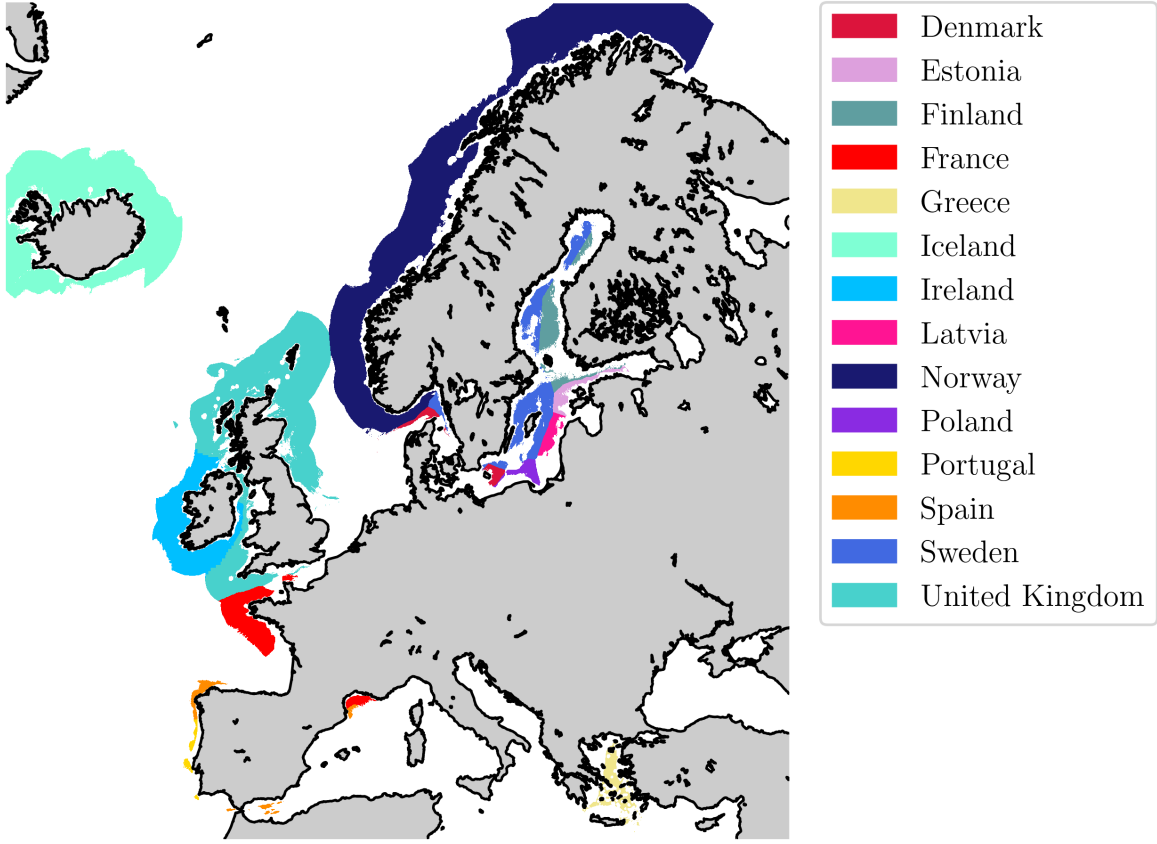


Figure 1.11. Potential FOW farm deployment sites in Europe.

The FOW potential in Europe is quite consequent but the harsh offshore environment requires a site-specific design of the system to enable overall cost reduction, as in [31], where specific floating substructure are designed for Italian sites. This emphasize the need for efficient design optimization methodologies and links with the following chapters of the thesis. This study primarily focuses on metocean and bathymetry data but does not address the complex aspects of maritime planning and the energy needs in Europe. Indeed, within the overall suitable area for FOW installations, certain regions might be designated for fishing activities, maritime routes, oil and gas extraction, protective designations, or other purposes. Furthermore, it is important to note the absence of information regarding soil types, the precise locations of major ports and industrial zones, and areas with the highest energy demand. These factors will undoubtedly play a crucial role in the deployment of FOW, but, unfortunately, fall outside the scope of this analysis.

1.3. The Floating Offshore Wind Energy Network

Over the years, different collaborative projects between industry and academia have been launched to address current and anticipated challenges. The **FLOAWER** is an **EU-funded** initiative that started in 2019, aiming to bring together leaders from the **FOW** landscape. It is supported by the Horizon 2020 programme under the Marie Skłodowska-Curie grant agreement N°860879. The network is organized around 13 early stage researchers, located in various academic institutions throughout Europe. The project focuses on **FOW** energy, which represents a unique opportunity for the **EU** but faces challenges primarily related to cost and technical development. As illustrated in Figure 1.12, the project involves a collaborative network of leading academic and industrial partners across the **FOW** energy sector, spanning the entire industry value chain. This includes experts in wind resource assessment, project development, and suppliers for various components such as wind turbines, floating platforms, mooring systems, among others.

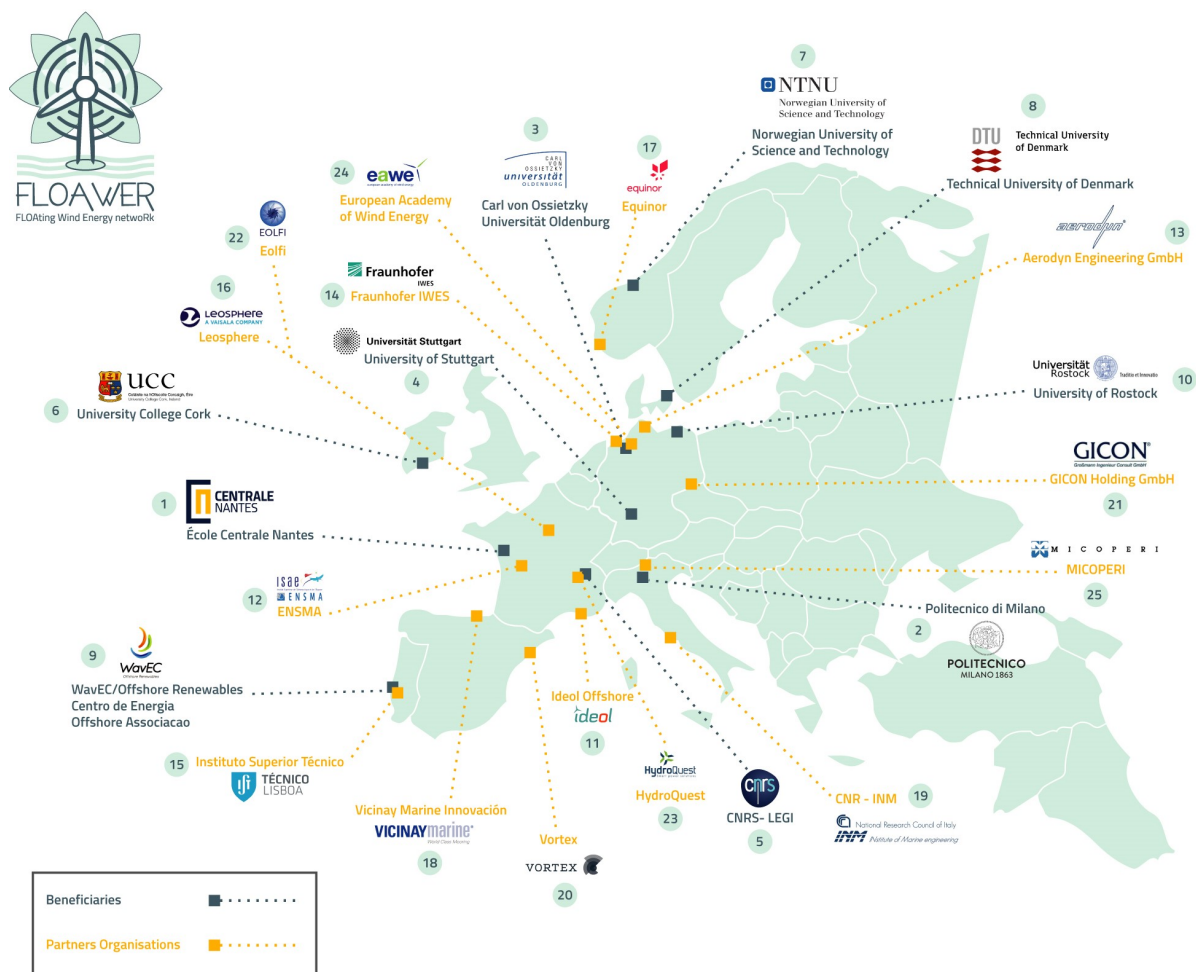


Figure 1.12. Academic and industrial partners involved in the **FLOAWER** project.

The main objective of the **FLOAWER** project is to train early stage researchers in the multidisciplinary fields essential for advancing **FOWTs** technologies and addressing challenges to enhance the **EU**'s competitiveness in this area. Each researcher focuses on an individual research program within various work packages, all aimed at reducing the **LCoE** of **FOW** energy. The project is structured into four scientific work packages, each addressing topics such as wind resource assessment, floater analysis, wind turbine dynamics, and system design. Further details on the network structure and research programs can be found on the project's website [32]. This thesis presents research conducted under work package 7, which aims to reduce the **LCoE** of **FOW** energy through the overall design of the **FOWT** system. The goal is to develop optimization tools by building on recent advancements, incorporating up-to-date numerical models, design processes, and cost assessment methodologies. These tools can help identify cost reduction opportunities and compare design alternatives from a techno-economic perspective. Other researchers in this work package focus on mooring system analysis, integrated design, and cost modeling. A key objective is to explore flexible and scalable design concepts for **FOWT** substructures and multi-use components. Many floating substructures, from prototypes to full-scale systems, use components with similar shapes and purposes, such as columns, pipes, braces, or pontoons. These components could be designed for adaptability across different substructures, enabling standardization in fabrication, reducing production and maintenance costs, and leveraging scale benefits for **FOW** energy. Additionally, the aim is to develop optimization tools specifically tailored for analyzing **FOWT** substructure designs that include these multi-use components.

1.4. Objective and Outline

This research was conducted within the **LWET** at the University of Rostock in Germany, which focuses on wind energy, particularly on numerical and experimental modeling related to both **OW** and **FOW** energy. The research group takes part in various academic projects and collaborations with industrial partners, including **GICON**, a key partner in the **FLOAWER** project, with extensive experience in designing and producing both bottom-fixed and floating foundations. The main objective of this thesis is to develop an optimization tool for **FOWT** substructure design and multi-use components that can be integrated into various design concepts. Leveraging synergies within the **FLOAWER** network, the focus is set on the specific floating foundation design developed by **GICON**, which has been a subject of prior research at the University of Rostock. Their innovative floating platform design serves as a notable example of efficient substructure design, featuring a flexible and scalable buoyancy body adaptable to other types floating foundations. The optimization work presented here extends the previous collaborative research carried out on this specific **FOWT** substructure design. This manuscript builds upon the research conducted within the framework of the **FLOAWER** project, including insights from public and private deliverables, and results published in peer-reviewed papers and conference presentations, such as [33–35] and [36].

This thesis and the following chapters are structured around three main tasks:

- *Provide a state-of-the-art relevant to **FOWT** substructure design optimization*
- *Develop a design optimization tool*
- *Reduce the **LCoE** for **FOW** energy*

This thesis addresses the broad topic of design optimization, specifically applied to **FOWT** substructures. Since one of the main goals is to develop a tool for the design optimization of the floating platform, it is important to establish the basics needed before developing and applying such a tool. The first part of this thesis presents the current state of the art related to the design optimization of floating substructures and their various components. It reviews the diverse types of floating platforms, identifies current design trends, and explores ways to reduce the cost of **FOW** energy. The main theories and engineering models for **FOWT** dynamics are introduced, and design methods are explored and presented. The literature on the design optimization of floating substructures is also reviewed. This concise but comprehensive review helps identify the main challenges in modeling such systems and assessing various substructure designs during an optimization process.

Subsequently, an efficient optimization framework for designing **FOWT** substructures and their multi-use components is presented. The main goal of this tool is to extend the work on the innovative floating platform developed by **GICON**, for which various analyses have been performed so far, but not optimization. The primary aim is to reduce the costs associated with the manufacturing of the floating foundation while considering its performance and structural strength. To achieve this, a specialized framework is developed, coupling an efficient optimization process with numerical models to assess the behavior of the platform and evaluate potential designs. Two main approaches are used to model the dynamics of the system and evaluate the structural integrity of its components. The numerical models developed and used in the framework to assess potential substructure designs are detailed, and the optimization algorithm implemented is thoroughly explained and validated. The complete framework and all its modules, along with their interactions, are presented and validated, highlighting the final structure's complexity and efficiency.

The final chapters of this thesis present two different study cases applied to the **FOWT** substructure developed by **GICON**, using the presented design optimization framework. This allows for the proposal of an optimized design for this particular substructure, which includes multi-use components and assesses the potential cost reductions that can be achieved. It also provides an opportunity to reflect on the performance and efficiency of the developed optimization framework and draw conclusions on the achievements of the thesis, the results obtained, and to offer recommendations for developing such processes, as well as suggestions for future work to enhance the framework presented.

State-of-the-Art

This chapter provides the state-of-the-art relevant to design optimization of FOWT substructures. It begins by presenting the main design concepts and introducing the classification of floating substructures. The chapter also explores the design philosophy and various methodologies used in the field. Current design trends are identified to better understand the development of future concepts aimed at reducing the cost of FOW energy. Next, the main theories and engineering models related to FOWT dynamics are discussed, laying the groundwork for the numerical modeling of these systems. The chapter concludes with a review of existing research on the design optimization of floating substructures. This review helps identify key challenges associated with FOWT modeling and evaluates different optimization techniques applied to the design of floating substructures. This state-of-the-art review serves as the foundation for the development of the design optimization framework presented later in this thesis.

2.1. Floating Offshore Wind Turbine Substructure

A FOWT consists of three main components: a floating substructure, a wind turbine, and a mooring system. Unlike bottom-fixed turbines which are directly embedded into the ground or the seabed, the substructure serves as a floating foundation for the wind turbine. To keep it in place, the platform is connected to a mooring system, which also helps maintain the overall stability of the system. Subsea dynamic and static power cables provide electrical connections, floating beneath the substructure before anchoring to the seabed and connecting to substations and the electrical grid further onshore. The floating substructure and mooring system are crucial for ensuring the stability needed to efficiently generate electricity, making their design a key focus area.

2.1.1. Classification

The early design concepts of FOWT substructures were inspired by existing floating structures, particularly those from the oil and gas and naval industries. The design, along with fabrication and installation processes, was adapted from established offshore practices. Despite the initial challenges of adapting to the specific demands of FOW energy, primarily feasibility at first and cost-effectiveness later, there has been substantial progress in research and development since the installation of the first floating system. This progress has led to the development of various design concepts, ranging from prototypes to commercial-scale farms, as documented in the literature. Floating platform configurations vary widely, and it is important to adopt the correct classification, as some design aspects vary with the floater type.

The classification of **FOWT** substructures originates from the oil and gas industry and the review of different design concepts proposed by industry and academia have been extensively addressed in the literature. One of the first classifications is introduced in [37], where the technical and economic challenges associated with the deployment of such systems are assessed. In [38], bottom-fixed foundations and some of the initial designs for **FOWT** substructures are reviewed in terms of technology principles and challenges. Additional market reviews focusing on **FOW** energy is conducted in [39, 40], highlighting the development timeline and various design concepts under development, with the highest commercialization prospects at that time. In [41], different floating substructures are evaluated for their suitability for farm level deployment using a multi-criteria decision analysis. More recently, concrete foundations of future **OW** projects, including floating substructures, are discussed in [42] to identify the challenges and future trends in their design. A complete and comprehensive review of the evolution of **FOWT** substructures is provided in [43], highlighting the design drivers and trends across a wide range of designs based on open-source data.

Floating substructures are usually categorized based on how the system achieves static stability, as this significantly impacts the design [37]. The literature commonly mentions three main stabilizing principles for **FOWT** substructures:

- **Ballast** stabilized platforms achieve stability by adjusting the weight distribution of the structure, which creates a righting moment that counters the system's displacements [37].
- **Buoyancy** stabilized substructures use buoyancy and water plane area distribution of the structure to generate the necessary righting moment [37].
- **Mooring** stabilized substructures maintain stability by the tensions in the mooring lines that generates the needed righting moment [37].

Throughout the development of the industry, various design concepts have been proposed, each with a wide range of characteristics and performance. Figure 2.1 illustrates this classification and provides a clear representation of the distinct design aspects of each substructure type. This diversity in **FOWT** substructure designs contrasts significantly with conventional bottom-fixed turbines and underscores the adaptability of floating technologies to harsh sea conditions. Generally, floating substructures uses one of the stabilizing principles or a combination of them, resulting in hybrid platforms. **FOWT** substructures are typically classified into four main categories:

- **Spar**
- **Semi-submersible**
- **Barge**
- **TLP**

For instance, spar platforms are long, cylindrical structures that achieve stability through ballast and are anchored to the seabed using catenary or semi-taut mooring lines. The significant weight of these platforms provides good stability, making them less susceptible to translational motions, although they can be more sensitive to rotational motions [43]. Spar platforms are typically used in deep waters and are well-suited to various sea states and harsh environments [37]. However, their large size and deep draft pose challenges for fabrication, transportation, and installation, making these processes both difficult and expensive [41].

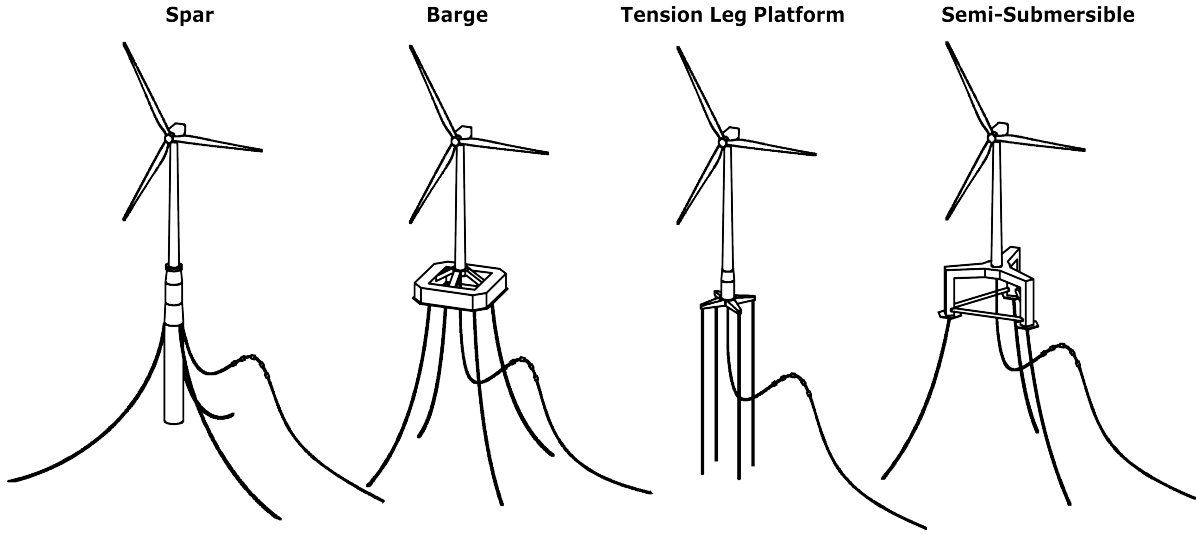


Figure 2.1. Illustration of the different type of FOWT substructures, from [44].

As the name suggests, semi-submersible substructures are designed to be partially submerged in water. They are composed of buoyant components, typically cylindrical or rectangular, connected by a support structure, such as braces or pontoons, and anchored to the seabed using catenary mooring lines. Due to their structure, semi-submersibles interact significantly with water and incoming waves, leading to complex system dynamics and relatively large vertical motions [43]. One of the main advantages of semi-submersibles is that they can be towed fully assembled, reducing the need for specialized vessels for transportation and installation, which lowers offshore operation costs [39]. However, the structural design of these FOWT substructures is complex, making manufacturing and maintenance operations quite expensive [41]. A comprehensive review of different semi-submersible design concepts, including both conceptual and operational projects, can be found in [45]. TLPs are also designed to be partially submerged but are anchored to the seabed with taut mooring lines that rely on tension for stability. They have a similar structural design to semi-submersibles, with buoyant components connected to form the FOWT substructure. The platform's stability is maintained by an excess of buoyancy countered by the tension in the mooring lines, which limits vertical displacement and system inclination [43]. TLPs are less affected by wave-induced motions, which reduces loading on the structure and allows for lighter and smaller substructure designs [46].

This substructure concept is promising because it can be efficiently constructed on-shore, towed out, and deployed offshore in various water depths, leading to significant cost reductions for the industry [39]. However, these systems require more expensive mooring arrangements and often need special purpose-built vessels for transport and installation due to their instability during these operations [11]. Currently, the number of installed FOWTs is limited, with only a few operational wind farms comprising a small number of turbines. Initial FOW projects used spar technologies, which provide a straightforward and stable solution that is relatively easy to manufacture, as demonstrated by the first commercial-scale wind farm (see Figure 1.4). Semi-submersibles and barge platforms have also proven to be viable technologies, with operational systems like the WindFloat substructure installed off the Portuguese and Scottish coasts, and upcoming projects in the Mediterranean Sea (see Figure 2.2a). Demonstration projects, pilot farms, and prototypes with alternative platform designs are also in place or planned, such as the Ideol barge with its unique moonpool design at the center (see Figure 2.2b). These diverse design approaches reflect the ongoing efforts by both industry and academia to develop FOWT substructures that meet future wind farm efficiency and cost-effectiveness criteria.

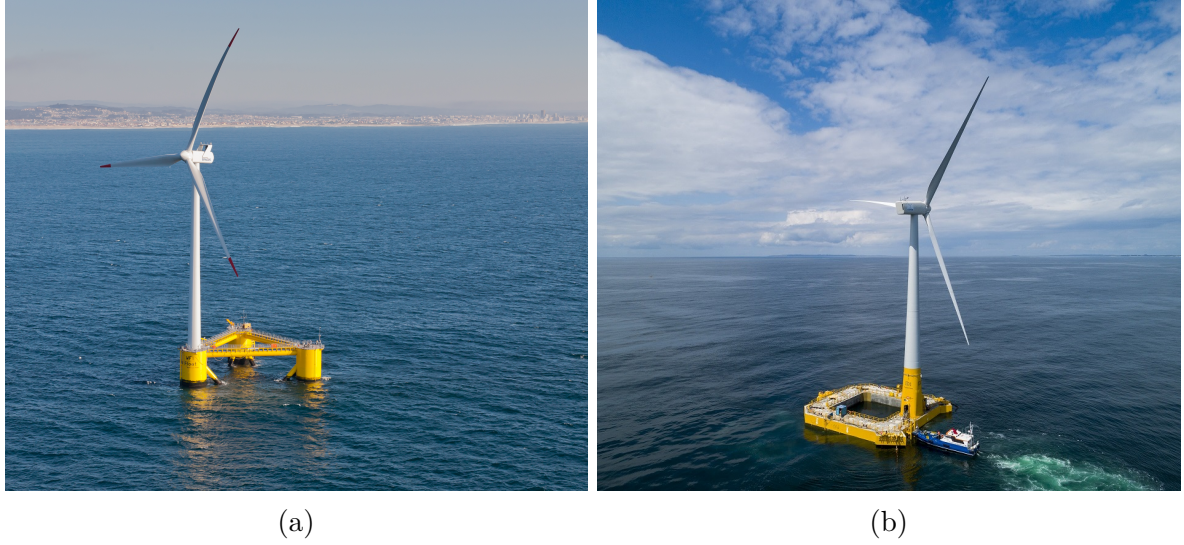


Figure 2.2. Installed FOWT examples with different substructure concepts, WindFloat semi-submersible (a) and Floatgen barge (b), respectively from [47] and [48].

The diversity in FOWT substructures, with varying aspects such as stability principles and design philosophies, leads to different dynamics within the floating systems. From spar and semi-submersible platforms to innovative barge platforms, and more recently TLPs, each design incorporates distinct stability mechanisms and operational characteristics. These differences require careful evaluation and adaptation throughout the design process to ensure both efficient performance and cost-effectiveness of the substructures. Figure 2.3 illustrates the stabilizing mechanisms involved in some of the main current FOWT substructure design concepts.

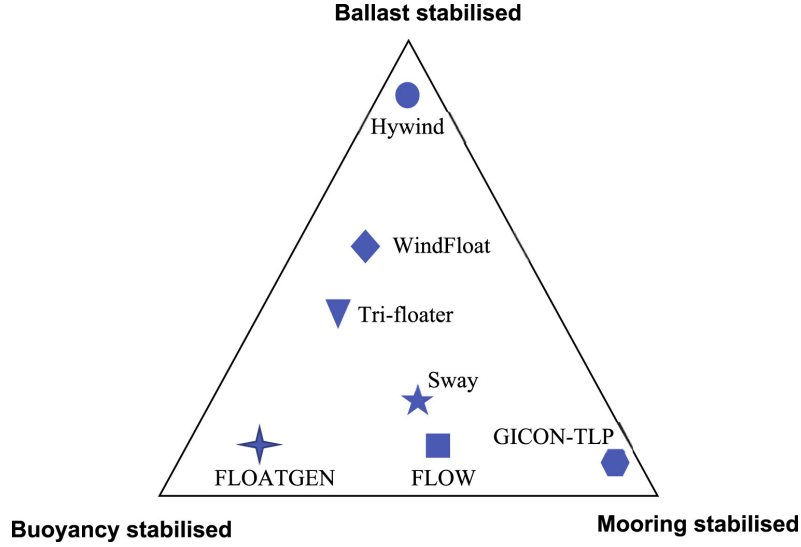


Figure 2.3. Stability mechanism in FOWT substructures for different design concepts, from [11].

2.1.2. Design process

Early FOW energy projects focused on showing the feasibility of different substructure concepts, while modern projects tend to find optimal designs. The EU-funded project LIFES50+ addressed the efficient design of very large FOWTs system and produced a complete review of FOWT technology and guidelines. In [49], an overview of FOWT design process and common practices are presented, with a focus on the floating support structure and the controller. The study reviewed the design procedures of numerous projects and reports, which all converged on a cyclical method involving continuous iteration loops between different levels of design fidelity. A generic design process was then established and is shown in Figure 2.4. This design process is divided into three essential phases: conceptual design, basic design, and detailed design. Iteration between these phases is crucial, as each iteration provides insights into the current state of the design and guides the process toward an improved design of the system under consideration. The design process generally begins with a very simple analysis, using simple engineering assumptions and physical principles. In [50], four innovative floating structure concepts designed by the INNWIND project partners are presented, along with the design assumptions used. The initial steps of their conceptual pre-design involve determining the platform's main properties, such as hydrostatic characteristics, preliminary geometry, overall dimensions, and mass distribution [51]. Many studies in the literature have conducted similar analyses, such as the early work on TLPs in [52–54], and more recent research in [46], which presents various standard TLP designs based on a parametric approach. The objective of this initial step is to ensure the stability of the floater with the mooring lines. In [55] several preliminary floating support structures concepts are investigated through techno-economic analysis and comparison that begins with preliminary sizing of the substructure.

Since the assumptions made in this phase influence subsequent design stages, they must be chosen carefully and adjusted as needed, for example, considering the wind turbine used or environmental data [49]. Another advantage of this approach is that it helps explore and narrow down the design space of potentially suitable substructures [56].

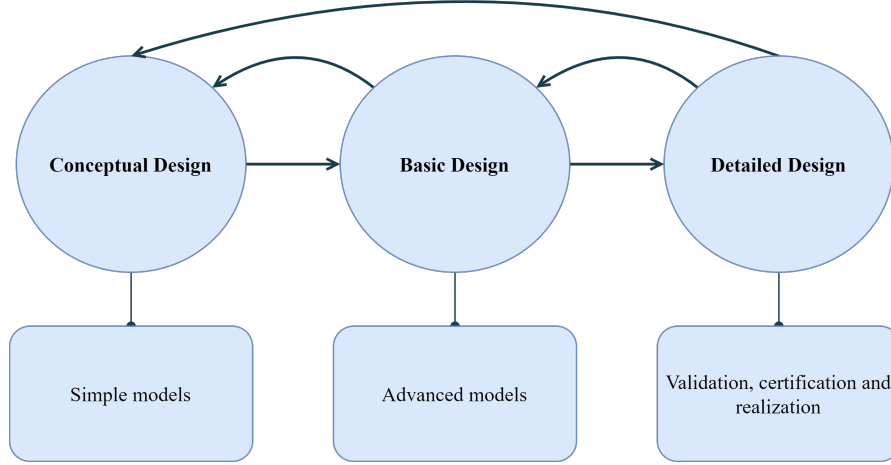


Figure 2.4. General design process for FOWTs, adapted from [49].

After the conceptual design of the substructure, a more advanced analysis of the entire system is initiated, using different **DLCs** which corresponds to potential environmental states that could occur during the system's lifetime. These cases can be defined by the designer or derived from standards and guidelines, which provide general examples for these load cases. This set of **DLCs** enables fully coupled simulations of the FOWT, including the mooring system and dynamic cables, to determine the system's response to environmental loads. The resulting loads and motions are then compared to the structure's strengths, and adjustments to system properties can be made as necessary. The standards outlined in [57] provide the basis for determining load values specific to these design loads, which are used throughout the design process, particularly for structural analysis. They also offer relevant combinations of external conditions and design situations to be analyzed, establishing a minimum set of **DLCs** to be considered for different scenarios of the system. Experimental procedures, such as scaled model testing, can also be initiated to validate the numerical models used and to increase confidence in the selected design. Once the scaled model and the associated numerical models (loads, modeling, simulations, etc.) are validated, the final stage of the process, the detailed design, can begin. The most precise and reliable environmental data, including metocean and geotechnical data from on-site measurements that describe wind, waves, currents, and soil conditions, are gathered and fed into the numerical model to refine the design. At this stage, certification of the design is crucial and certification companies must be involved no later than this point. The validation and demonstration of the system's design at full-scale or as smaller scaled prototypes in real environmental conditions no matter what requires certification.

2.1.3. Design trends

The main objective of current designs is to reduce the **LCoE** (Levelized Cost of Energy) of the overall system to make it competitive with fixed offshore wind projects, and even onshore wind projects [51]. Cost reduction has been demonstrated in the oil and gas industry through the transition from fixed to floating substructures, along with more standardized designs, optimized fabrication processes, and easier assembly, transportation, and installation [39]. The offshore wind industry is following a similar path but still faces challenges such as design complexity, fabrication constraints, and a lack of consideration for manufacturing, supply chain, and installation procedures [49].

Manufacturing, transport, and installation of **FOWTs** are seen as areas with high potential for reducing **LCoE**. Therefore, the design should not only focus on technical aspects but also on industrial factors that impact the overall design [49]. For instance, while **TLPs** meet static stability requirements with a taut mooring system, this system cannot be used during transport from the port to the operational site [56]. Conversely, spar-type floaters have excellent stability and hydrodynamic properties but are unsuitable for shallow waters due to their deep draft and need to be ballasted offshore, which requires specialized vessels and crews [58]. The use of special vessels is a significant cost driver and should be minimized. Substructure designs should also consider shipyard dimensions and the ability to assemble the floating system at port before transport, which is considered a major advantage [49]. Many new floating substructure concepts take into account industrial considerations, as well as transportation and installation challenges.

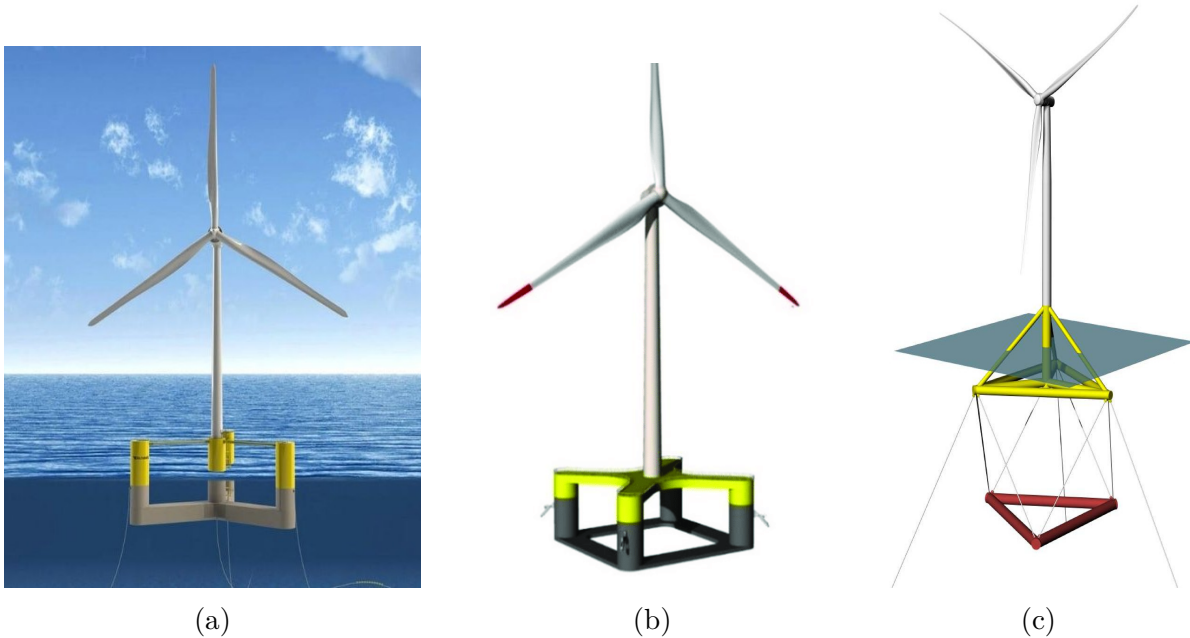


Figure 2.5. The VoltturnUS (a), Nautilus (b) and Tetraspar (c) design concepts for **FOWT** substructure, respectively from [59], [60] and [61].

The TetraSpar design by Stiesdal aims to industrialize floating substructures by simplifying manufacturing and installation processes. Its design relies on modular components that are widely available in the current wind energy supply chain and suitable for mass production, which provides a significant advantage in reducing the costs of FOW energy [56]. The substructure is towed from the port in a semi-submersible configuration and converted into a spar configuration by ballasting a counterweight attached once offshore, resulting in significant cost reductions through a straightforward fabrication, transportation, and installation process [61]. In [62], a hybrid platform called the CENTEC-TLP is examined in its free-floating condition, using a design that combines the stability of a barge-type floater with the hydrodynamic advantages of TLPs. Other disruptive floating substructure concepts designed to reduce costs include X1Wind, a self-orienting floating platform, and EOLINK, a single-point moored substructure. Both floaters are designed with industrialization and installation considerations in mind, resulting in lighter and scalable structures.

The development and evolution of new TLP designs for cost reduction are discussed in [63–65]. The GICON®-TLP substructure design emphasizes modularity to maximize flexibility within the supply chain and allows the choice of different suppliers for cost efficiency. Modular components, such as buoyancy bodies and connecting pipes, are designed for serial fabrication processes. Preliminary designs of these multi-use components, like the buoyancy bodies, are detailed in [66]. This floater can be transported by standard tugboats and benefits from a single-step installation process without the need for expensive installation vessels, as highlighted in [67]. The overall system design was also updated using steel-reinforced concrete elements to further reduce the LCoE. Historically, many FOWTs substructures were built using steel, following the established practices of fixed offshore wind and leveraging the extensive experience of the steel industry [39]. However, designers are increasingly using concrete in their concepts, resulting in heavier but cheaper structures, as concrete can be up to ten times less expensive than steel [49]. Additional benefits of using concrete include more sustainable production and greater resistance to corrosion. Although there is less experience with large-scale concrete fabrication compared to steel, both materials are considered optimal choices for substructure design to reduce costs [49].

Looking forward, FOWTs may be integrated with other marine renewable energy harvesting systems, such as solar, wave, and tidal energy [56]. This integration aims to reduce the cost of energy by sharing infrastructure, such as floaters and electrical grid connections, with FOWTs. Many recent design studies have focused on these multi-use platforms, such as [68], which presents the basic design of a special cost-effective energy hub energy platform for offshore wind farms. Numerous ongoing investigations and projects, like the InSPIRE project, aim to achieve competitive LCoE with integrated wave and wind semi-submersible floating platforms. Current research also introduces concepts of platforms supporting multiple turbines to further reduce costs, such as Hexicon’s two-turbine floater. It is important to note that LCoE cannot be entirely generalized, as it is highly project-specific and depends on numerous factors [56]. However, considering LCoE is crucial in the early stages of the design process and remains an important focus throughout the refinement of substructure designs.

2.2. Floating Offshore Wind Turbine Modeling

The analysis of offshore marine structures is a broad field with long-established theories widely applied in shipbuilding, oil and gas, and more recently, in the **OW** industry. The numerical modeling of a **FOWT** is a multidisciplinary problem that involves various fields of study, including mechanics, hydrostatics, hydrodynamics, and aerodynamics, among others. The dynamic behavior of the system is significantly influenced by environmental loads that interact with the entire structure, as illustrated in Figure 2.6a. Environmental conditions such as wind, waves, currents, water level variations, and marine growth are site-specific factors that induce loads, affecting both the static properties and dynamic response of the floating substructure. Floating platforms are exposed to a harsh environment and are typically treated as rigid bodies which exhibit six degrees of freedom, as shown in Figure 2.6.

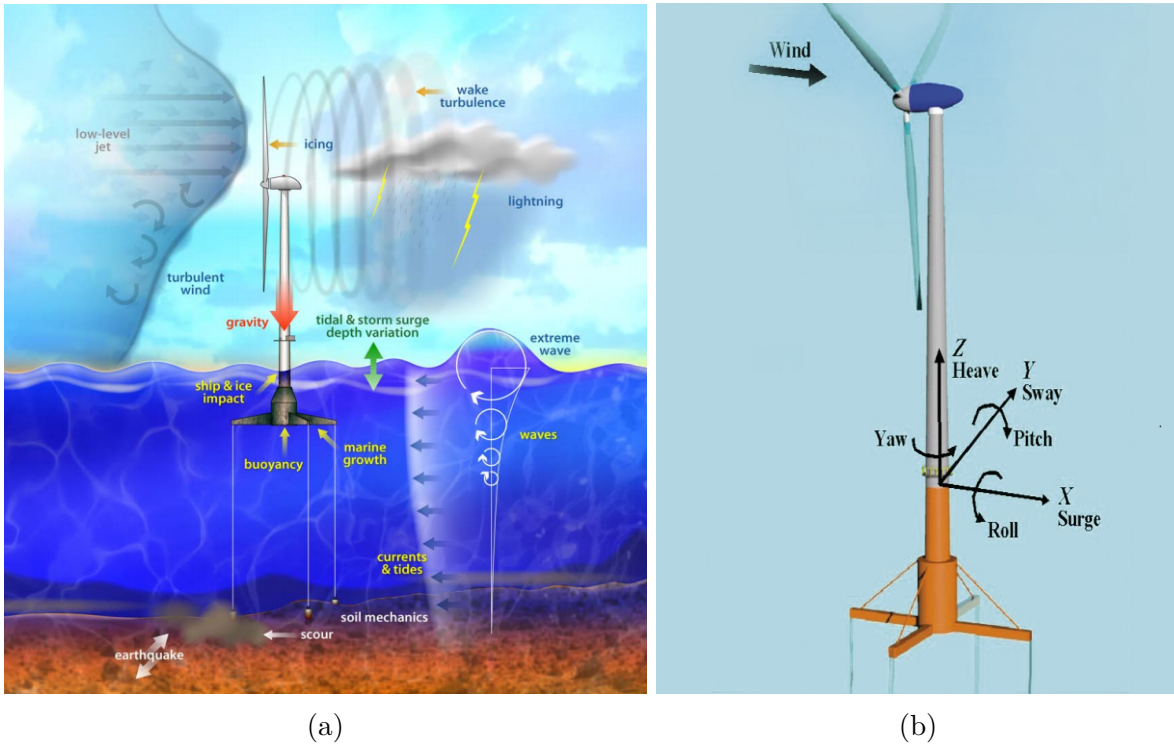


Figure 2.6. Offshore environment and resulting loads on the **FOWT** system (a) and its degrees of freedom (b), from [69].

These degrees of freedom are commonly named: surge (translation along the x-axis), sway (translation along the y-axis), heave (translation along the z-axis), roll (rotation around the x-axis), pitch (rotation around the y-axis), and yaw (rotation around the z-axis). Depending on the platform type, motion in one or more degrees of freedom may be compliant or restrained, which impacts the system's dynamics and must be considered in dynamic studies. The recommended practice [70] provides guidance on these dynamics for the main substructure concepts discussed earlier.

There are various approaches in the literature for writing the equations of motion for a FOWT system, each derived from the mass, acceleration, and total forces on the floating body. Generally, the equation of motion of the floating system is expressed, as in [71]:

$$(\mathbf{M} + \mathbf{M}_a)\ddot{X} + \mathbf{B}\dot{X} + \mathbf{K}X = F_{ext}, \quad (2.1)$$

where X is the system's state, $\mathbf{M}$ is its mass matrix, $\mathbf{M}_a$ is the added mass matrix, $\mathbf{B}$ is the damping matrix, $\mathbf{K}$ is the stiffness matrix, and F_{ext} represents the external forces acting on the system. To assess the dynamic response of floating systems due to environmental forces, two main methods are widely adopted in the literature: FD and TD analysis [45, 56, 72, 73]. For linear systems, a floating body subjected to a periodic load of a single frequency will exhibit an excitation response at the same frequency, commonly defined in traditional ship and ocean engineering as the RAO [72]. In FD analysis, the transfer function between the system's motion amplitude and the wave amplitude for a given frequency and degree of freedom can be derived. Although RAOs are primarily used to estimate the system's steady response to waves, they are frequently utilized in FOWT analysis [56]. FD methods have been extensively applied in the ship and oil & gas industries, as well as in numerous research studies on offshore floating structures [52, 55, 74, 75]. Due to their low computational cost for dynamic analysis, they provide a practical solution, particularly when dealing with optimization. However, FD analysis cannot capture dynamic characteristics or model transient loading events [45], which can be critical for certain substructure designs or for achieving precise system modeling.

TD analysis allows for the consideration of nonlinear phenomena and the assessment of transient regimes of the system. It can estimate the time response of the FOWT dynamics, as well as the loads applied on the structure. Statistical analysis can then be performed to obtain significant values of each parameter, such as the maximum, minimum, or mean displacement of the structure in one degree of freedom [56]. In [76], a TD analysis and FD simulations of a FOWT system were conducted to compare the results of the two approaches. Both methods showed relatively similar results for the linear rigid body, suggesting that a FD approach can be useful in the early stages of the design process. However, nonlinear effects impacting the system's response for certain degrees of freedom could not be captured with the linear FD model, as noted earlier. It is also important to mention that TD calculations generally involve higher computational costs compared to FD computations.

2.2.1. Aerodynamics

Aerodynamic loads are accountable for the power production of the wind turbine, the steady component is generated by the mean wind speed and variations are due to wind shear and turbulence [77]. The most common, and relatively easy way to compute aerodynamic loads on a wind turbine is by using the BEM theory [78].

The method is based on the conservation of momentum and energy equation of different control volumes of the two dimensional flow around the blades elements of the rotor [73]. Lift F_l and drag F_d forces can be derived for a given blade element width Δr , chord length c and incoming flow velocity u , as in [78]:

$$\begin{cases} \Delta F_l = \frac{1}{2} C_l \rho u^2 c \Delta r, \\ \Delta F_d = \frac{1}{2} C_d \rho u^2 c \Delta r, \end{cases} \quad (2.2)$$

where ρ is the air density, C_l and C_d are respectively the lift and drag coefficient which are functions of the angle of attack and the Reynolds number. Since it was first suggested, the method have known many improvements to account for tip and root effects (Prandtl's tip loss correction factor), turbulent wake state, three dimensional and viscous effects as well as empirical corrections [72]. The BEM approach is simple, computational friendly and has been widely used in the wind industry, however due to the particular motions of FOWT and the unsteady inflow it is subject to, the system is prone to more complex aerodynamic loads that are not captured by this method [73].

Recently, more efficient but computationally expensive aerodynamic models have been developed to overcome BEM method limitations, using for instance potential flow theory and CFD methods [78]. More accurate CFD methods seemed too computationally expensive and they will remain reserved for detail calculations and detail design stages. However, with the development of computer technology, CFD became a strong tool to analyze the dynamic responses of FOWT [72]. The very computationally expensive, direct numerical simulation approach, consist in solving the full Navier-Stokes equations considering all relevant length scales for turbulence model and requiring a large and refined mesh for the studied domain [79]. Potential flow theory and BEM method seems more suitable integrated load simulation and design approach [79].

2.2.2. Hydrodynamics

Hydrostatic and gravity loads act on floating structure's static stability and also impact the structure's dynamic response to its environment. Generally hydrostatic restoring forces are studied using linear hydrostatic approach assuming small displacement of the immersed floating structure when compared to the structure's characteristic dimensions [71]. Hydrostatic stiffness matrix, $\mathbf{K}_h$ can be defined, computed and used for hydrostatic force F_h acting on the system as:

$$F_h = -\mathbf{K}_h X. \quad (2.3)$$

Hydrostatic restoring forces and moments are nonlinear, particularly for heave, roll, and pitch, and these non-linearities can increase the motion dynamic response amplitude, these effects have been studied in [80] and [81] where time dependent hydrostatic restoring stiffness is investigated.

In addition, theory for second order hydrostatic can be found in [71]. Hydrodynamic loads become more important when dealing with FOWTs, and depends on the design of the substructure and the environmental conditions it is exposed to [77]. One aspect of hydrodynamic analysis is modeling sea states and waves, with a complete review of the basic concepts and modeling techniques available in [82]. Usually, most common wave models used for coupled analysis are irregular Airy waves which is applicable when the wave height is small compared to water depth and wave length [70]. Two modeling approach are mainly used for the computation of hydrodynamic load acting on FOWTs, potential flow theory and Morison's empirical equation [83]. Additionally, CFD techniques can also be used to compute hydrodynamic loads on the substructure and have been recently the focus a many research work as in [84, 85]. For floating bodies, large and small components are distinguished based on their interactions with waves: large elements experience radiation and diffraction effects with inertia-dominated loads, while small bodies have negligible diffraction and are dominated by viscous effects [82]. The Keulegan-Carpenter is a dimensionless number often used as an indication of the relative importance of drag versus inertia forces [86], and it is defined as:

$$K_c = \frac{2\pi A}{D}, \quad (2.4)$$

where A is the wave amplitude and D the characteristic length of the floating body. For high values of this number drag can be linearized and the use of Morison's equation is recommended. [87] proposed semi-empirical formulas, widely called Morison's equation, to asses the hydrodynamic load calculation of slender cylindrical bodies. Wave exciting force can be estimated assuming in line forces by a superposition of two components, the inertia force and the quadratic drag force to get the following resultant force per unit length for a cylindrical segment of diameter D , as in [86]:

$$F_{hydro} = C_a \rho \frac{\pi}{4} D^2 \ddot{u} + C_d \frac{1}{2} \rho D u |u|, \quad (2.5)$$

where C_a and C_d are the dimensionless inertia and drag coefficients, respectively, ρ is the mass density of the fluid, and u is the time-dependent flow velocity. Drag and inertia coefficients depend the Reynolds and Keulegan-Carpenter numbers, which describe the flow field around the body being considered. These coefficients are generally determined through experimental or empirical approaches, and recommended values can be found in various standards, such as [29]. For small Keulegan-Carpenter numbers ($K_c < 3$), inertia forces dominate, making potential flow theory applicable as drag forces can be neglected [86]. As offshore substructures grow to support larger wind turbines, other hydrodynamic effects, like diffraction and radiation, become significant and are not accounted for by Morison's equation [79, 88]. Morison's equation is best suited for submerged slender structures and does not consider wave diffraction, which can be important for certain floating substructures [83]. Linear potential flow theory includes diffraction and radiation effects and is valid for small to moderate waves [89]. Radiation accounts for forces from waves radiating away from an oscillating body, while diffraction deals with forces from waves scattering around the structure [82].

This linear approach only addresses first-order problems, ignoring higher-order terms like quadratic components, which simplifies computations but can still be accurate in some cases [90]. Potential flow theory can be extended to include mean drift forces or second-order loads which are proportional to the square of wave amplitudes and arise from the interaction of wave pairs [89, 91]. These interactions lead to forces associated with so called **QTF** at the sum and difference frequencies of the wave pairs [90]. For softly moored floating foundations, like semi-submersible platforms, second-order theory is recommended for evaluating hydrodynamic responses [45]. One limitation of potential flow theory is its neglect of viscous loads [92], but these can be included by adding viscous damping terms using an adapted Morison's equation on certain parts of the structure [88]. **CFD** tools can also compute hydrodynamic loads on **FOWT** substructure by solving the Navier-Stokes equations to determine the instantaneous pressure distribution on the substructure [73], although this approach requires significant computational time and cost. In addition to the expensive computational cost of **CFD**, meshing of the domain and the structure adds complexity to this approach.

2.2.3. Mooring analysis

As for **FOWT** substructure classification, mooring lines are categorized with respects to their shape and ability to keep a system in a given position. any different configurations exist concerning mooring lines ranging from layout, number of lines, parameters, material or additional buoy and weight, and a good overview can be found in [93, 94]. There are two main types of mooring systems: catenary and taut mooring lines, or sometimes a combination of both, as shown in Figure 2.7.

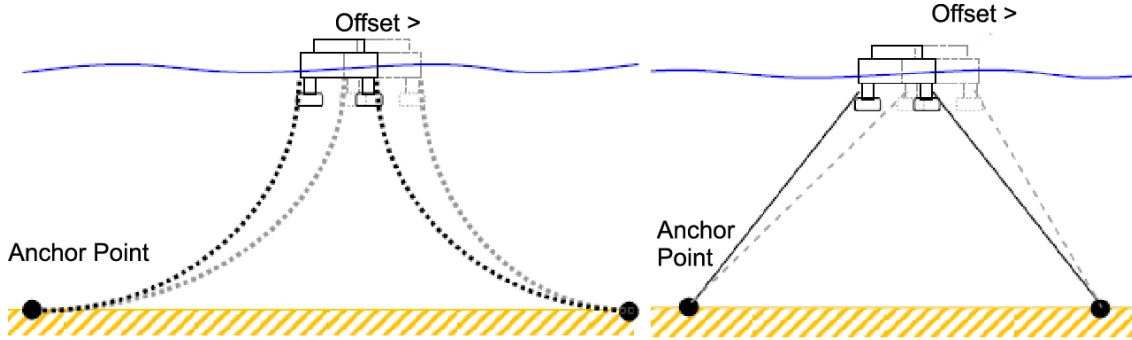


Figure 2.7. Main mooring line configurations for offshore structures that are commonly used for **FOWTs**, with catenary (left) and taut (right) lines, from [95].

In shallow waters, the dynamic effects of mooring systems are often neglected due to the negligible mass of the lines, but in deeper waters, especially for next-generation **FOWTs**, these dynamics become crucial [79]. Mooring line modeling typically uses three approaches: force-displacement, quasi-static, and dynamic models [45]. Force-displacement models treat mooring lines as springs, providing a simple way to assess restoring forces, but they ignore dynamic effects like inertia, drag, and vortex shedding [79, 96].

Quasi-static models capture nonlinear behavior, including seabed friction and axial stiffness, but still exclude dynamic effects [96]. They balance line weight with tension and solve nonlinear equations for line shape and internal forces, making them suitable for quick assessments [45, 69, 78]. However, for a coupled analysis of mooring line dynamics with wind turbine responses, fully dynamic models, such as lumped mass or finite-element methods, are needed; these consider line position, velocity, and acceleration under various forces, but at the cost of increased computational complexity [45, 78, 96].

2.2.4. Structural analysis

Structural analysis is performed to study the capacity of the system to sustain external loads for different environmental conditions and operational state which are usually describe in FOWT design standards such as [97]. When considering the substructure, it is subject to static loads such as gravity or hydrostatic pressure, as well as dynamic loads due to the wind and wave environment [78]. Instead of analyzing the platform as rigid body, it is often discretized using a number of finite elements allowing the approximation of field quantities such as stress and strain in the overall structure [78].

For the structural analysis of floating platforms FEA is extensively used and is a common practice where three-dimensional model with shell elements or one-dimensional beam model with beam elements are usually used [73]. Beam Theory, applicable for long and slender elements assuming small deflections, is a classical description of the relationship between the applied load and the deflection of the structure [78]. Shell elements, applied to thin plate structure can capture flexural stresses which are not considered in a beam models [78]. For more detailed design or when local stress concentration phenomenon occurs local finite element analysis using solid elements is needed. A global analysis of the model is firstly done to evaluate boundary conditions of the studied area and applied in a more detailed model. Due to the large size and displacement of the structure of the supporting floating platform analysis of elastic responses should be considered [73], as in [98] where hydroelastic interactions between the flexible substructures and the surrounding fluid are considered.

2.2.5. Numerical tools

Numerical models for floating platform dynamics need to integrate structural dynamics, aerodynamics, hydrodynamics, and mooring lines to accurately assess the system's behavior. Many of the tools used for the modeling of FOWT originated from oil and gas, aeronautics, and have been adapted from onshore wind turbine analysis to offshore applications, often requiring coupling with additional software to address hydrodynamic effects. Several reviews have evaluated these tools, including those by [99, 100], who assessed available simulation codes, and [79], who highlighted modeling challenges and needs particularly for FOWT simulations. More recently [88] and [78] provided an overview of the tools used for design and optimization and detailed available design codes.

All methods come with their own set of assumptions, accuracy and computational cost, as shown in figure 2.8 which gather the main numerical models and compare in terms of numerical fidelity and efficiency. A key tool in FOWT modeling is OpenFAST, a time-domain aero-elastic-hydro-servo coupled dynamic model widely used in offshore wind design. Developed by the National Renewable Energy Laboratory (NREL), OpenFAST includes modules for aerodynamic, hydrodynamic, and mooring line modeling, using methods like corrected BEM theory for aerodynamics and a combination of potential flow theory and Morison's equation for hydrodynamics [73]. It supports various mooring line models, including quasi-static and finite-element dynamic approaches [78]. OpenFAST can also integrate with third-party frequency-domain codes like WAMIT, AQWA, or WADAM for hydrodynamic properties. Other time domain software for the modeling and simulation of FOWT are also often used and mentioned in the literature such as BLADED, Deeplines, FLEX5 or HAWC2. Due to the many design challenges and the complexity of these simulation tools, verification and validation of their accuracy have been performed by the research community. Research tasks were developed by the IEA to address this question by conducting different projects called Offshore Code Comparison with the aim of comparing dynamic computer codes and models used to design offshore wind turbines and floating support structures.

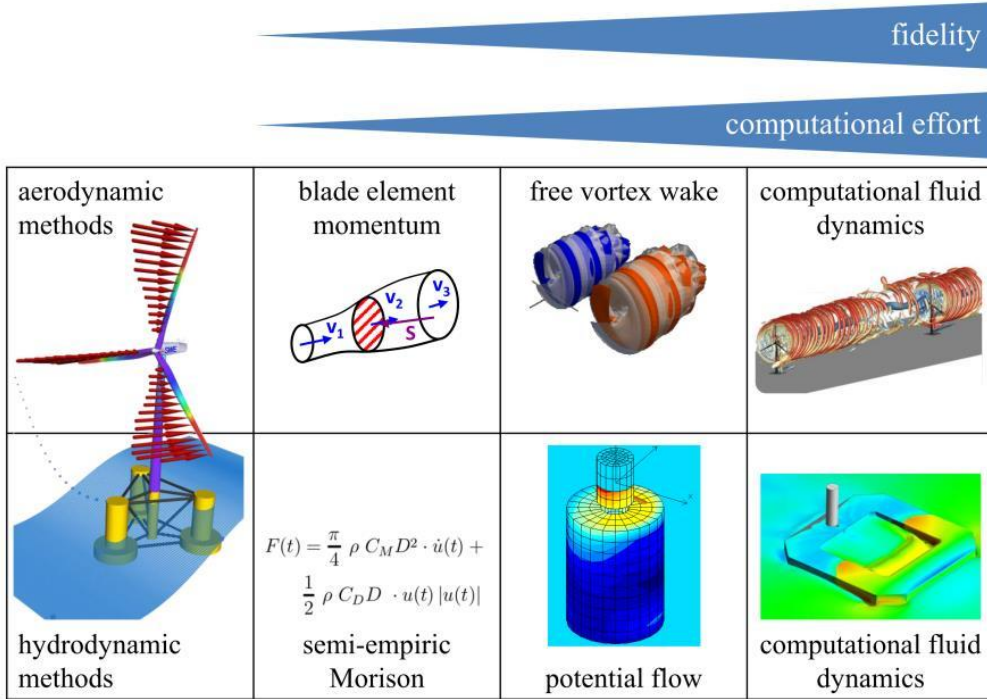


Figure 2.8. Main numerical models for aerodynamic and hydrodynamic analysis of FOWT systems with comparison on their numerical fidelity and efficiency, from [49].

2.3. Design Optimization of Floating Offshore Wind Turbine Substructure

Optimization is a broad topic widely used in engineering and other disciplines. This section introduces only the basics of optimization, with more detailed information on design optimization available in [101, 102]. Every design optimization process begins with defining the mathematical problem, which is then solved by an optimization algorithm. The design variables, which represent a specific state of the system, are selected from a bounded design space and remain fixed during each iteration. The quality of a design is measured by an objective function, which is minimized or maximized depending on the goal. Constraints, categorized as equality or inequality constraints, also play a key role. To summarize, for an optimization problem with n_x design variables, n_g inequality constraints, and n_h equality constraints, the general mathematical statement can be expressed as shown in [102]:

$$\begin{aligned}
&\text{minimize:} && f(x), \\
&\text{subject to:} && x_i^L \leq x_i \leq x_i^U \quad \forall i \in \llbracket 1; n_x \rrbracket, \\
&&& g_j(x) \leq 0 \quad \forall j \in \llbracket 1; n_g \rrbracket, \\
&&& h_k(x) = 0 \quad \forall k \in \llbracket 1; n_h \rrbracket,
\end{aligned} \tag{2.6}$$

where x represents the set of design variables, x^L and x^U denote the lower and upper limits of the design space, f is the objective function, g_j is an inequality constraint and h_k an equality constraint. Multi-objective optimization problems involve multiple objective functions $f \rightarrow (f_0, \dots, f_n)$, leading to a so-called Pareto front that allows the assessment of trade-offs between the different objectives that are being minimized. While optimization problems are often framed to minimize objective functions, maximizing a function can also be achieved by minimizing its negative. Defining the objective functions is often challenging and is crucial for properly establishing the mathematical optimization problem in order to solve it. To solve such problems, many methods and algorithms have been developed and their review can be found in [102], where a global classification of optimization algorithms is given and detailed.

The design optimization framework presented in the following chapter of this thesis is intended for designing FOWT substructures to reduce material costs and ultimately lower the LCoE for FOW energy. The optimization process faces challenges due to the harsh offshore environment, which introduces complex loads and non-linear effects that complicate the analysis. Its development requires integrating numerical models with mathematical optimization processes, adding an extra layer of complexity. The optimization process is central to the framework, driving it towards the optimal solution by minimizing objectives while respecting constraints. The choice of the optimization algorithm and balancing accuracy and computational efficiency is critical, as detailed models improve accuracy but slow down the process, while simpler models allow for quicker iterations but may overlook key system aspects [103].

2.3.1. Literature review

Early FOW energy projects were mainly aimed at proving the feasibility of concepts, but current projects focus on optimizing designs at both system and component levels. FOWT systems are complex, with optimization work that can target various components, such as rotor blades, towers, foundations, and mooring systems, to enhance performance or reduce costs. Given that the floating platform is a significant cost driver, many optimization studies focus on substructure design optimization due to its potential for cost reduction [103]. In the literature, many studies have been performed on the design optimization of the different components of floating offshore wind systems. A complete and detailed review work with regards to the design optimization of the foundation for OWTs can be found in [103]. Early research work with regards to floating offshore systems used parametric studies in order to screen different design possibilities such as in [53], where simplified frequency-domain analyses is performed to evaluate mainly TLP designs. One of the first optimization tools developed for floating offshore wind, named Windopt, is presented in [104]. The tool is dedicated to spar type platforms and allows for an integrated design optimization of the foundations as well as the mooring system and dynamic power cable using a gradient-based method with the objective to minimize the cost of the whole system.

Later work also performed parametric studies, like in [105], where fully coupled time-domain simulations are performed, or in [106], where a parametric study of cylindrical floating platforms considering both concrete and seawater ballasted cylinder with different combination of draft is conveyed. Another framework for floating support structure design optimization is described in [96]. It consists of, first, a geometric parametrization scheme that allows to span a wide design space covering the three main floater concepts already mentioned before: spar, TLP and semi-submersible type platform. In addition, the mooring system is also taken in consideration as it varies with the platform's geometry and the water depth. The performance of a given candidate is evaluated using a FD analysis and the optimization process is conveyed using a particular evolutionary algorithm, capable of identifying multiple non-global optima in the design space. Later in [107], a hydrodynamic-based optimization process for floating support structures is presented. Instead of considering the design space in a conventional geometric way, it is represented by a linear combination of the hydrodynamic performances of a diverse set of basis platform geometries. Similar work can be found in [108], where a multi-objective design optimization work is presented. Improvements regarding the modeling of the system is brought by using a coupled approach in the FD and a Kriging-Bat optimization method, another evolutionary algorithm. Recently, a fully integrated design optimization framework for spar type floater is developed and presented in [109]. Another evolutionary algorithm is used to solve the multi-objective optimization problems that is considered in this study. A framework for conceptual design optimization of floating platform is presented by [110]. This time the optimization process uses a gradient based method namely the sequential quadratic programming method. The objective functions are here again the cost of the system calculated based on its geometric characteristics.

Some examples of optimization work regarding other components of a floating offshore wind energy system can be found in [111], where the hydrostatic preliminary design of dynamic inter-array cables is performed through a parametric study where water depth and cable length are varied. In [112], a framework for multi-objective optimization of the mooring systems is done using a surrogate model coupled to the so called Non-dominated Sorting Genetic Algorithm in order to minimize both the cost and cumulative fatigue damage of the mooring system. With the goal to improve the model floating offshore system, [113] conducted a parametric study where a semi-submersible substructure as well as the wind turbine controller are optimized, with the objective to minimize cost and response to wind and wave excitation. The floating system is modeled using a simplify model developed in the thesis work [92]. It is important also to highlight the European project LIFES50+, which ended in 2019 and dealt with efficient substructure design for very large FOWT. The objectives of the projects were successfully achieved by delivering two optimized floating foundations designed for 10 MW turbines through numerical and experimental validation, as well as qualitative deliverable regarding the efficient design of floating substructures [49].

2.3.2. Genetic algorithms

In the literature reviewed in the previous section, evolutionary algorithms, particularly **GAs**, are widely used for FOWT substructure design optimization. These algorithms, inspired by biological evolution, operate with a population of individuals, each representing a potential design solution, which evolve through the design space. Typically, **GA** follows the general procedure illustrated in Figure 2.9, where the population evolves iteratively through the optimization process through three main steps: selection, crossover, and mutation.

1. **Selection** is based on natural selection, where more favorable individuals of the population survive longer and are kept within the population.
2. **Crossover**, inspired by chromosomal crossover is the exchange of genetic material between two individuals, the parents, resulting in one or more offspring.
3. **Mutation** mimics the genetic mutation phenomenon, where a change in the gene sequence of an individual occurs randomly.

Every iteration, the fitness of each individual in the population is evaluated based on their objective and constraint values, allowing the individuals to be ranked. This ranking allows the selection strategies that determine which individuals are retained in the population or chosen to undergo genetic operations. These operations drive the population towards areas of the design space with higher fitness, ultimately aiming to identify the optimal solution to the problem. While most **GAs** follow this general procedure, there is significant flexibility in how these steps are implemented, leading to a variety of genetic operators and evolution strategies which are well gathered and detailed in [102].

GAs are effective for both constrained and unconstrained optimization problems, particularly when derivatives of the objective and constraint functions are either unavailable or too complex to obtain [102]. They are particularly suited for so called "black box" optimization problems, when the function to be optimized is unknown or too complex to define explicitly, as they do not require gradient information. Instead, they explore the design space by evaluating candidate solutions based on performance, iteratively improving them over time through the evolutionary process. This capability makes **GAs** ideal for optimizing complex systems, such as floating platform designs, where the optimization involves numerous variables and constraints that are not easily expressed in closed-form equations.

In **FOWT** substructure design, softwares and numerical solvers typically provide only input-output relationships, making gradient-based or explicit optimization methods complex. **GAs** are particularly suited for these types of problems as they do not require gradient information. Instead, they explore the design space by evaluating candidate solutions based on their performance, iteratively evolving towards better solutions through the optimization process. This makes **GAs** ideal for complex optimization problems with multi-modal, non-linear, or computationally expensive objective and constraint functions, which are common in engineering design optimization such as with floating platforms. **GAs** are extensively reviewed in [114], where the analysis of the different genetic operations, including selection, crossover, and mutation techniques is performed. Additionally, the review addresses various constraint-handling methods and considerations, along with the arrangement of these operations to optimize performance in different applications.

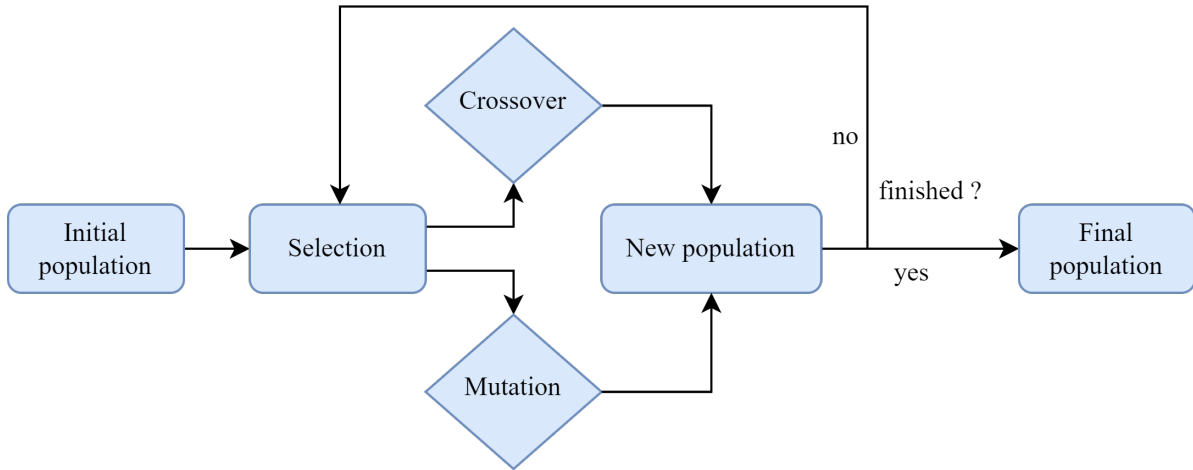


Figure 2.9. General structure of **GAs**.

Development of an Efficient Design Optimization Framework

3

This chapter introduces an efficient optimization framework for the design of FOWT substructures and their multi-use components. To begin with, the main objective behind the development of this tool is given and the GICON®-TLP substructure is presented and detailed. Indeed, the development detailed in this chapter is specifically focused on this substructure design which integrates an adaptable buoyancy body used as a multi-use component. Then, the different numerical models developed and used in the framework to assess potential substructure designs are detailed. This includes two different approaches for modelling the floating system but also puts a focus on the components of the substructure and its components. The optimization algorithm implemented is also thoroughly explained, as the choice behind some aspects of the optimization are justified to make it efficient. Finally, the implementation of the framework and all the modules interacting with each other are presented, highlighting its complex final structure. The development of the proposed design optimization framework is one of the main objectives of this thesis and serves later in the next chapter for the obtained results.

3.1. Objective

The main goal behind the development of the presented optimization framework is to extend the work carried out on the innovative design of the GICON®-TLP. The objective of this optimization work is to reduce material costs associated with the manufacturing of the floating substructure, particularly its buoyancy bodies, which could be adapted as multi-use components. By minimizing the structural mass of the platform and its components, this will contribute to lowering the overall cost of the system and in the end reduce the LCoE of FOW energy. The design optimization of FOWT substructures plays a crucial role in the overall performance and economic viability of floating wind farms. However, attention must be paid to ensure the structural integrity and correct dynamic behavior of the system are maintained.

The GICON®-TLP is considered here because it serves as a notable example of efficient substructure design, integrating multi-use components, mainly its flexible and scalable buoyancy body that could be adapted to other floating foundations. As seen in the state-of-the-art, the design of FOWT substructures is a multidisciplinary task bringing along many Challenges. The different stages in the design process and the wide range of numerical tools involved, each with its own computational efficiency and precision, makes the integration quite complex. The proposed optimization framework is intended to be used in the preliminary phase of the design process. However, it should also be able to model the system with sufficient precision for potential application in later stages of design.

3.2. The GICON[®]-TLP

In recent years, there has been a growing trend towards optimizing substructure designs for cost-effectiveness. This has resulted in the development of more streamlined and modular floating platforms, made up of standardized components that can be prefabricated and assembled efficiently in docks, enabling mass production and reducing the costs of fabrication and installation for each unit. In 2009, the GICON group and their partners started a research project regarding the development of a floating foundation, eventually leading to the evolving design of the so called GICON[®]-TLP. The platform is designed to be suitable for shallow and deep waters and aims to address the cost related challenges associated with FOW energy. The development path of the GICON[®]-TLP has been documented in various research [64, 115] and is illustrated in Figure 3.1 to highlights the major design modifications it has undergone.

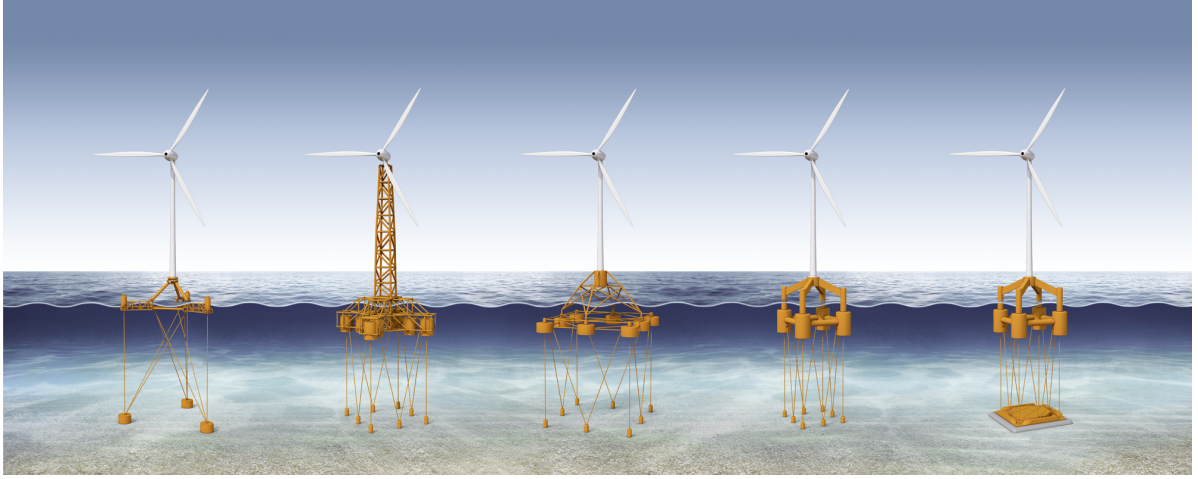


Figure 3.1. Development path of the GICON[®]-TLP, from its early concepts (left) to its latest design (right), from [64].

The innovative design of the GICON[®]-TLP intends to offer technical solutions to the recurrent challenges current floating foundation face. This TLP consists of a steel and concrete structure featuring four buoyancy bodies that are arranged in a rectangle shape. These buoyancy bodies are connected to each other by a bracing structure made up of horizontal pipes. The substructure is then connected to the wind turbine transition piece by vertical and diagonal pipes. The latest design of the GICON[®]-TLP, and the one that will be considered for the present optimization work is shown in figure 3.2 This particular substructure is indeed a TLP but can also be considered as an hybrid semi-submersible bringing advantages compared to other floating substructure types. As a TLP the system relies on the stiffness of the mooring system to cope with the offshore environment and the overturning moment caused by the turbine thrust while operating. This allow to design smaller infrastructure with reduced draft, when compared to other design concepts, to support the huge multi MW OWTs that will be operational in the future.

On the other hand, the GICON[®]-TLP offers a solution to the challenges faced by conventional TLPs during installation. Due to their inherent stability mechanism, TLPs face challenges before being moored to the seabed, and requires expensive special operation vessels for transportation and installation. The GICON[®]-TLP features a lowerable gravity anchor that is particularly useful during these processes and eliminates the need for expensive special operation vessels. During the transport the whole system acts as free floating structure and can be towed out on the deployment site, before blasting the anchoring system and stabilizing the FOWT by tensioning the mooring system. Research work have already been performed on the installation process of this substructure, mainly in [67, 116, 117].



Figure 3.2. Illustration of the design of the GICON[®]-TLP for a multi-MW wind turbine and its simple installation process, from Daniel Walia (LWET).

In addition, the GICON[®]-TLP is oriented towards bringing solutions to the problems leading to expensive manufacturing of floating substructures. The current approach for the manufacturing of offshore structures is done by considering steel welding techniques which are both time-consuming and expensive. The TLP offers alternative by the possibility of using Ultra High Performance Concrete elements resulting in a lighter and more efficient structural design. This approach, commonly used in bridge engineering, can enhance the structural strength and life time of the support structure and are also quite competitive in terms of price. Therefore it significantly reduce the manufacturing costs compared to traditional welded steel FOWT substructures. Research work have already been performed on the material used for this substructure, mainly in [63, 65, 118].

The present design optimization work extends the research already carried out by the research group at the University of Rostock on the **GICON®-TLP** substructure. So far, this work mainly focused on numerical modelling, design validation and experimental tank tests, on the different life aspect of the substructure, as in [116, 119, 120]. Figure 3.3 highlights the setup of the scaled model of the **GICON®-TLP** which was tested in the offshore basin of the École Centrale de Nantes, and for which the results were compared to numerical models and showed good agreement.

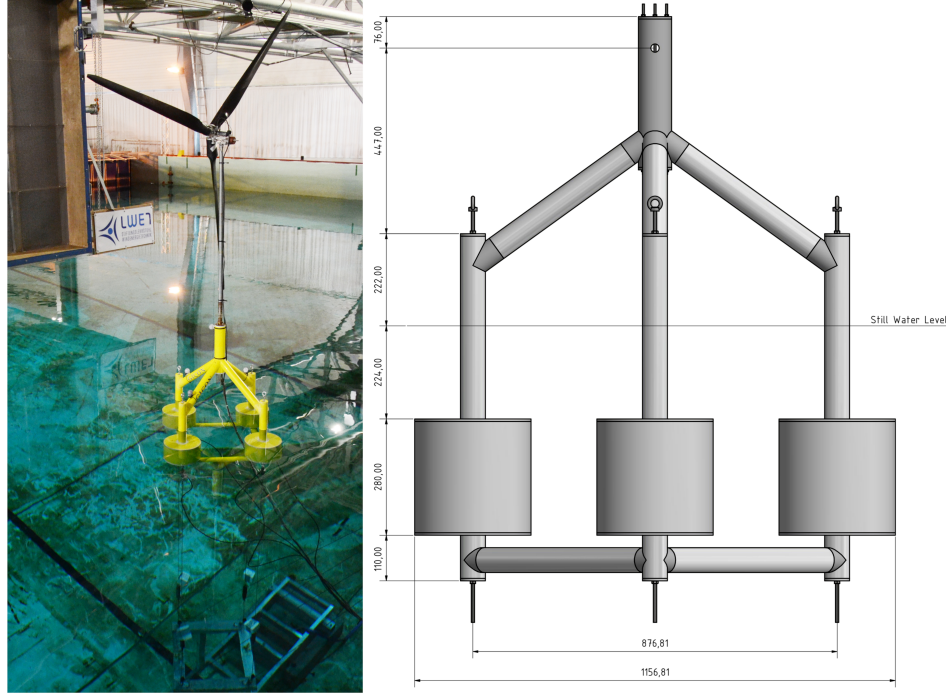


Figure 3.3. Scaled model (1:50) of the **GICON®-TLP** during the experimental tank tests performed at École Centrale Nantes in 2020, from [120].

3.3. The Universal Buoyancy Body

The majority of current floating substructure designs involve buoyancy bodies in their configuration, which have similarities particularly for **TLP** and semi-submersible platforms. Many floater concepts presents cylindrical buoyancy bodies, like the **GICON®-TLP**, which nowadays includes four cylindrical shaped buoyancy bodies in its design. In order to reduce costs, the design of this buoyancy body is thought to be scaled in a wide range and be integrated as a standardized component in the primary structure of **FOWT** foundations. The design of floating substructure components is usually similar to classical ship structures design. The fabrication process takes place at yard and requires large number of stiffeners and welds to ensure structural strength and stability of the structure. This approach leads in the end to high manufacturing time and costs, and therefore to higher **LCoE**.

With the development of the **GICON[®]-TLP** substructure globally aiming to reduce cost of **FOW** energy, a particular buoyancy body design was proposed in [66]. The **UBB** is characterized by a simple design, inspired by wind turbine tower and monopile designs. The **UBB** consists of four main components such as an inner and outer pipe as well as an upper and lower cover, shown in Figure 3.4b. The pipes are made out of thick steel sheets with a similar fabrication process as for monopiles and wind turbine towers, and provides a sufficient stiffness without the use of classical ship's design stiffeners.

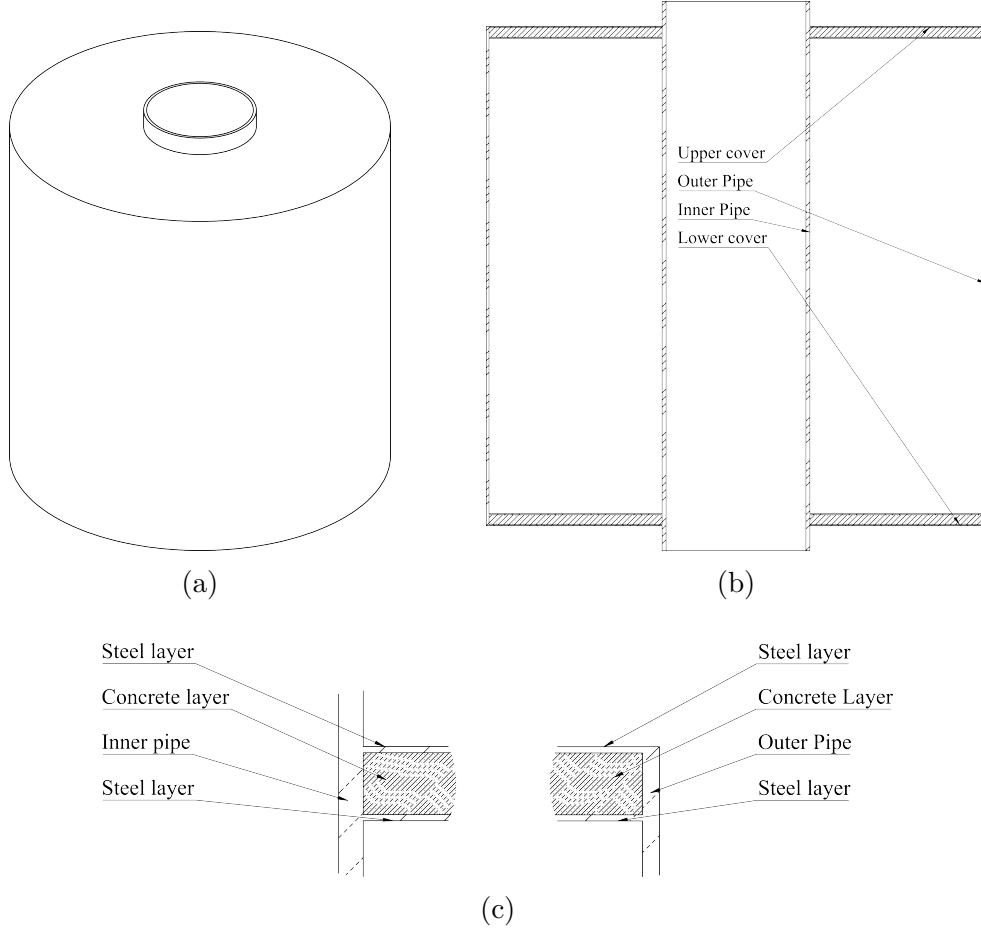


Figure 3.4. Three-dimensional (a) and sectional (b) view of the **UBB** and details of the steel and concrete layers of the covers (c).

The covers also provide stiffness to the structure with a steel and concrete layer type design at the top and bottom on the buoyancy body. The details of the covers' structure are shown in Figure 3.4c. The **UBB** can be integrated into the surrounding substructure of a given floater at the top and at the bottom of the inner pipe by specific connector, without altering the given structural characteristics of the floating platform. This particular structural design globally enables a relatively fast manufacturing process while keeping a certain level of structural efficiency.

On one hand, the structural mass of the buoyancy bodies increases and therefore the material costs also, while, on the other hand, manufacturing time and total cost drop. Another advantage of the **UBB** is that its design can be adapted for future and already existing floating substructure concepts regardless of their type, as many different floating platforms include cylindrical buoyancy bodies in their structural design. Eventually, the **UBB** could be manufactured in dedicated facilities in relatively high quantity according to different substructure types, standards, offshore sites or any other criteria relative to the manufacturer or project developer. A complete presentation of the **UBB** design and a first structural analysis can be found in [66].

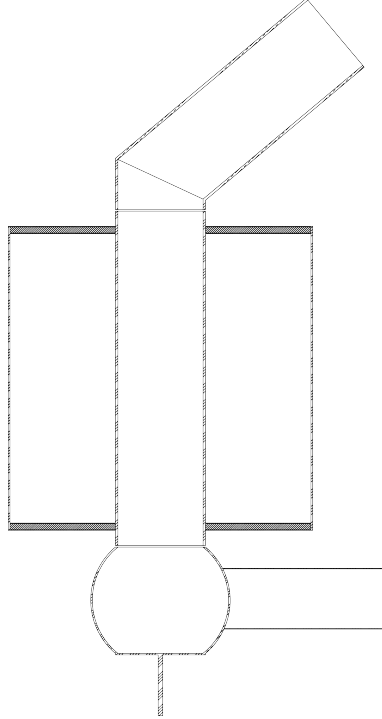


Figure 3.5. Structural integration of the **UBB** as multi-used component into the design of the **GICON[®]-TLP**.

3.4. Numerical Models

To model the **GICON[®]-TLP** and assess potential substructure design configuration, two numerical modelling approaches are used. Essentially, a structural model of the buoyancy body component is used in order to assess the structural integrity of this multi-use component and its integration in the **GICON[®]-TLP**. To understand and assess the behavior of this substructure and other dynamic properties of the whole system, a dynamic model of the **FOWT** is also implemented. These two different numerical models as well as the implementation for the particular design of the considered system are detailed in the next sections.

3.4.1. Structural model

As seen in the literature, structural analysis of any given structure is a complicated task and comes at a given computational cost. Here only the **UBB** is considered as the focused of the analysis is set on its integration into floating substructures. To perform the structural analysis of a given design and verify its structural strength, the **FEA** tool Ansys is used. Similarly as in [66], a global model is created as a 0.1° section of the **UBB** with adequate symmetrical boundary conditions at the cutting areas (u_θ , rot_r and rot_z are locked to zero in global cylindrical coordinate system). The model of the **UBB** implemented in Ansys Mechanical is shown in Figure 3.6 as well as the mesh used for the study. Ansys SOLID186, 3D high order 20 nodes solid element is used for meshing the geometry as they are well suited for hexahedron elements and to model irregular meshes. The connection of the upper end of the inner pipe to the surrounding floater structure is modeled as a boundary condition with translational degrees of freedom locked in all three directions (u_r , u_θ and u_z are locked to zero in global cylindrical coordinate system). As shown in Figure 3.6, rope loads F_{moor} are applied at the nodes of the bottom of the inner pipe as a fixed force (red arrows) and hydrostatic pressure are applied as pressure with height gradient at the outer surface of the **UBB** (multi-colored arrows). The height gradient comes from the water elevation as the **MSL** (from which the top of the **UBB** is defined) plus a given fixed wave height H_s from the environmental conditions considered.

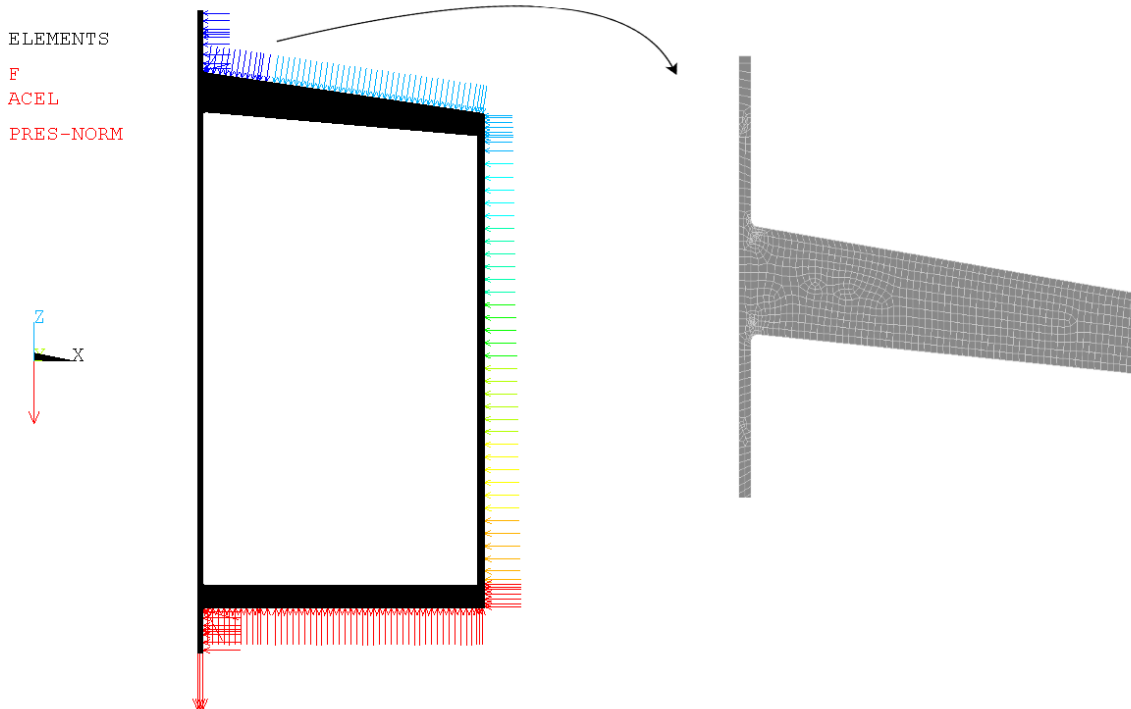


Figure 3.6. Structural model of the **UBB** in Ansys Mechanical, with boundary conditions (left) and the mesh of the covers (right).

As concrete and steel are the two main materials used in the fabrication process of the UBB, Table 3.1 summarizes these materials main physical properties used in the present study, particularly the values implemented in Ansys for the structural analysis. The stress distribution in the global structure is obtained after the structural analysis performed, and can be checked as a constraint. After some postprocessing operations, the maximum nodal stress can be obtained and checked against a given limit. In this study the equivalent Von Mises stress is used as it is often chosen for max yield checking, and values for steel can be obtained from offshore design standards such as [97, 121] for buckling analysis. In addition, it is interesting to monitor the buoyancy force of the body as sufficient vertical force should be provided to keep the substructure afloat and steady. Therefore it is computed and can be monitored and checked for constraints. The buoyancy force F_b generated by the structure is computed as:

$$F_b = (\rho_w V_d - \rho_s V_s - \rho_c V_c) g, \quad (3.1)$$

where V_d is the displaced volume of sea water due to the immerge structure, ρ_w , ρ_s , ρ_c are respectively the sea water, steel and concrete density, V_s and V_c respectively the total volume of steel and concrete material used for manufacturing the UBB and g the gravity.

Table 3.1. Material properties implemented in Ansys Mechanical.

	Density (in $\text{kg} \cdot \text{m}^{-3}$)	Young's modulus (in GPa)	Poisson's ratio
Steel	7850	210	0.3
Concrete	2400	35	0.2

3.4.2. Dynamic model

To model the dynamics of the GICON[®]-TLP for a typical multi-MW OWT, the RAFT open-source code is used (available at [122]). This tool is capable of evaluating both the static properties and the dynamic response of FOWTs in the FD, providing a comprehensive analysis of the system's behavior under varying environmental conditions. While a detailed description and the theoretical foundation of RAFT can be found in [123], the tool still lacks full documentation, which presents certain limitations for users. In this thesis, the focus is on highlighting the specific aspects of modeling the GICON[®]-TLP relevant to the design optimization framework introduced. Within RAFT, the system is modeled as a rigid body with the common six degrees of freedom: surge, sway, heave, roll, pitch, and yaw. The dynamics are represented in the FD, allowing the FOWT system to respond linearly to each excitation frequency and the superposition of responses using Fourier series of complex amplitudes. As a result, both the response X and the external forces F_{ext} are expressed as a mean value plus a frequency-dependent term.

The complex amplitude of the system's response $\tilde{X}$ at a given frequency ω is obtained by solving the generic equation of motion of the **FOWT** system, as in [123]:

$$(-\omega^2 \mathbf{M} + i\omega \mathbf{B} + \mathbf{K}) \tilde{X}(\omega) = \tilde{F}_{ext}, \quad (3.2)$$

where $\mathbf{M}$, $\mathbf{B}$ and $\mathbf{K}$ are respectively the system's total mass, damping and stiffness matrix, and $\tilde{F}_{ext}$ the complex amplitude of the external excitation forces. The **FOWT** system is simplified but still includes the different components with a certain level of details. The **RNA** is represented as a single rigid body with defined mass and inertia coefficients as well as an offset from the tower centerline. The rotor of the turbine is represented with three identical blades with specific dimensions (chord, twist angle and prebend) and distributed aerodynamic properties (lift and drag coefficients). The tower is modelled using a cylindrical member with distributed nodes mainly defined by diameters and thicknesses. Similarly, the substructure is modelled using a combination of different members. **RAFT** offers a wide range of possibilities for modeling cylindrical or rectangular shaped members with tapered sections, ballast, caps and bulkheads. This comes particularly handy here, as the design of the **GICON[®]-TLP** and the **UBB** are globally made of different cylindrical pipes. The substructure model implemented consists of three main members, one for each of the horizontal, vertical and diagonal pipes and are shown in Figure 3.7, as well as the details for the modelling of the **UBB**.

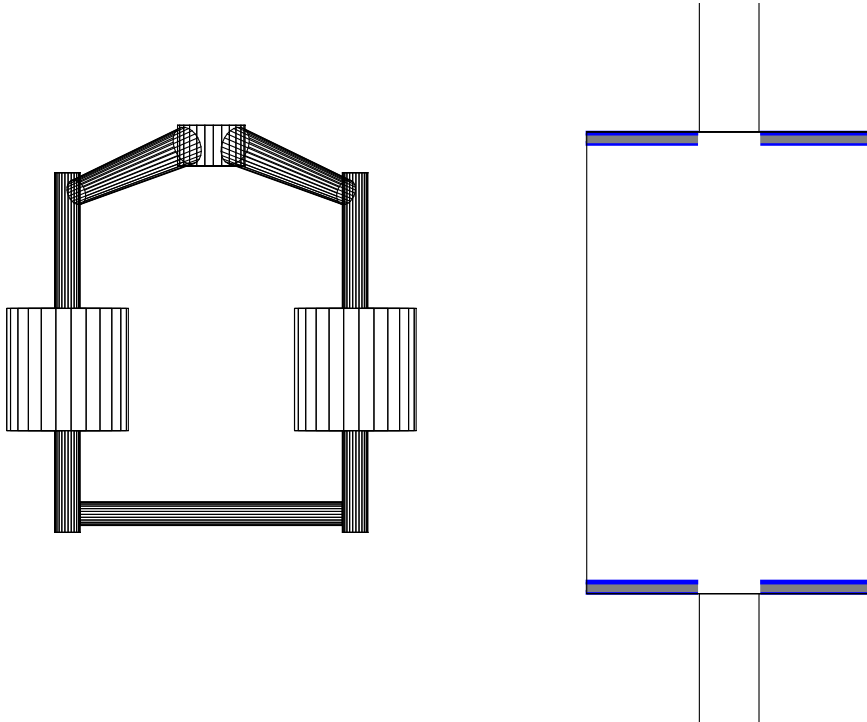


Figure 3.7. Member-based modelling in **RAFT** of the **GICON[®]-TLP** (left) and details for the **UBB** and its covers (right).

All cylindrical members are defined according to their diameters and thicknesses with a particular geometry for the vertical pipe to account for the UBB structure. In addition to the variation in diameter, concrete and steel caps are added to consider for the covers and their inertial effects. The horizontal and diagonal pipes are defined similarly as a straight and tapered cylinders respectively. The members are rotated and duplicated to form the rectangular shape GICON®-TLP. In addition, another member is used to consider the upper node which acts as the transition piece between the substructure and the turbine. The mooring system is simply defined using defined lines and points fixed to the seabed and to the substructure that are characterized by their material, geometrical, mass and stiffness properties.

Initially, the mass properties of the system are computed by adding the contributions of the tower, the RNA and also of all the members of the substructure to get each component its mass and inertia matrix. Similarly, the buoyancy and hydrostatic stiffness properties of each members in the water are obtained and then summed for the whole floating substructure. Theses properties are then summed across all components of the system giving the total mass and stiffness matrices, $\mathbf{M}_{tot}$ and $\mathbf{K}_h$, as in [123]:

$$\begin{cases} \mathbf{M}_{tot} = \mathbf{M}_{tower} + \mathbf{M}_{rna} + \sum_i \mathbf{M}_{m_i}, \\ \mathbf{K}_h = \mathbf{K}_h^g + \sum_i \mathbf{K}_h^{m_i}, \end{cases} \quad (3.3)$$

with $\mathbf{M}_{tower}$, $\mathbf{M}_{rna}$, and $\mathbf{M}_{m_i}$ representing the mass and inertia matrices of the tower, the RNA, and a given member, respectively. The hydrostatic stiffness matrix $\mathbf{K}_h^{m_i}$ of a given member of the substructure (except those fully out of the water) is computed by considering its displaced volume V_d , water plane area A_{wp} and coordinates x_{wp} and y_{wp} , and its moments of inertia I . Additionally, the hydrostatic stiffness due to the total FOWT weight, $\mathbf{K}_h^g$, is considered and computed using the total mass of the system m , as in [123]:

$$\mathbf{K}_h^g = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -mgz_{cg} & 0 & 0 \\ 0 & 0 & 0 & 0 & -mgz_{cg} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}, \quad (3.4)$$

$$\mathbf{K}_h^{m_i} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \rho g A_{wp} & \rho g A_{wp} y_{wp} & -\rho g A_{wp} x_{wp} & 0 \\ 0 & 0 & \rho g A_{wp} y_{wp} & \rho g (I_x + V_d z_{cb}) & -\rho g A_{wp} x_{wp} y_{wp} & 0 \\ 0 & 0 & -\rho g A_{wp} x_{wp} & -\rho g A_{wp} x_{wp} y_{wp} & \rho g (I_y + V_d z_{cb}) & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}.$$

The frequency-domain dynamics of the FOWT is assumed to operate around a specific position $\bar{X}$, which is defined as the mean steady state of the system. This position is obtained by solving the following static equilibrium equation derived from equation 3.2, as in [123]:

$$\mathbf{K}_h \bar{X} = \bar{F}_{ext} + \bar{F}_{moor}(\bar{X}), \quad (3.5)$$

where $\bar{F}_{ext}$ are the mean external forces applied on the system, $\bar{F}_{moor}$ the non-linear reaction force of the mooring system (accounting for the effective mooring stiffness) and $\mathbf{K}_h$ the total hydrostatic stiffness. In this study, the mean external force considered is due to wind loads, as waves mean drift loads are not considered by RAFT at the moment. Current loads can also be considered and computed as mean drag force using a power law to get the current velocity as a function of the substructure's draft, but is not considered here. The mean aerodynamic forces and moments on the rotor are computed using CCblade [124] a steady state BEM solver which is incorporated in RAFT. Given a mean wind speed, blade properties and the position of the rotor (mainly pitch), the solver computes the mean rotor power and torque in order to get the mean aerodynamic loads. To account for the mean mooring reaction force on the platform, the mooring system is modeled using MoorPy [125] a quasi-static model, which solves the standard catenary equations of each mooring line and the mean mooring for a given position of the system.

The static equilibrium equation 3.5 is then solved by iteratively updating the position of the FOWT and the mean loads acting on it, until convergence to an equilibrium position, which is then defined as the mean offset of the system and its operating pont. The frequency-domain dynamics of the system are then determined by solving equation 3.2 with the following matrices, as in [123]:

$$\begin{cases} \mathbf{M} = \mathbf{M}_{tot} + \mathbf{M}_a^{aero}(\omega) + \mathbf{M}_a^{hydro}(\omega), \\ \mathbf{B} = \mathbf{B}^{aero}(\omega) + \mathbf{B}^{hydro}(\omega), \\ \mathbf{K} = \mathbf{K}_h + \mathbf{K}_{moor}(\bar{X}), \\ \tilde{F}_{ext} = \tilde{F}_{hydro}(\omega), \end{cases} \quad (3.6)$$

where $\mathbf{M}_a^{aero}$, $\mathbf{M}_a^{hydro}$ and $\mathbf{B}^{aero}$, $\mathbf{B}^{hydro}$ are respectively the added mass matrices and damping matrices from the contributions of the rotor aerodynamics and substructure hydrodynamics, $\mathbf{K}_{moor}$ the mooring system stiffness matrix about the mean offset of the system and $\tilde{F}_{hydro}$ the wave excitation force. To do so, some of these terms need to be linearized in order to form a linear matrix equation that can be solved iteratively until convergence of the systems' response. The linearization process concerns mainly the aerodynamics of the rotor and the hydrodynamic damping of the substructure as well as the drag contribution to the wave excitation force. The rotor aerodynamics effects on the system's response are modeled using the derivative of thrust with respect to wind speed information from the aerodynamic solver.

RAFT allows the control of the turbine to be modelled and impact the response of the system, by considering fluctuations in the rotor speed and blade pitch, using linearized equations of motion for the rotor's dynamics and the controls. Without control, the aerodynamic contribution are mainly a damping term which accounts for the platform surge and pitch motions. When the control of the turbine is activated, the torque and nacelle-velocity feedback controls are taken in consideration and impact the aerodynamic damping contribution and adds a added mass term due in the equation of motion. As the focus is set on modelling the substructure, the details behind the aerodynamics modelling are not fully tackled and can be found in [123, 124]. The hydrodynamic approach used here is based on the relative form of the Morison equation for transverse flow across a cylindrical strip, accounting for wave and body velocity. The substructure's members are discretized into different strips of different geometry and wave kinematics, and for each strip the hydrodynamic force can be computed, as in [123]:

$$\Delta F_{hydro} = \left(\rho(1 + C_a) \frac{\pi}{4} D^2 \dot{u} - \rho C_a \frac{\pi}{4} D^2 \dot{v} + \frac{1}{2} \rho C_d D (u - v) |u - v| \right) \Delta l, \quad (3.7)$$

where Δl is the strip length, D its diameters, C_a and C_d the local added mass and drag coefficients, u and v respectively the wave and body velocity. For each strip, with a given orientation, geometry and wave kinematics, a local added mass and damping matrix as well as an excitation term (including inertial and drag contributions) is computed and then summed for to get the hydrodynamics of each members and for the whole substructure to obtain the total related matrices.

Determining the drag and added mass coefficients for the different members depends on the geometry and the flow regime, meaning that for different environmental conditions, these coefficients would vary. Many different studies and offshore standards have tried to calibrate or come with a suggestion with empiric laws for their values. For the scope of this optimization work, the variation of these coefficients with different waves condition is not considered and fixed values are taken. The particular values of the hydrodynamic coefficients used in **RAFT** for each of the submerged members of the substructure are given in Table 3.2. This is also done with considerations of the previous work carried on the modelling of the **GICON[®]-TLP** which assumed particular value for the drag and added mas coefficients for the horizontal and vertical pipes but also for the **UBB** with its larger diameter.

Table 3.2. Hydrodynamic coefficients of the **GICON[®]-TLP** implemented in **RAFT**.

	C_a	C_d
Vertical pipe	1.0	0.65
Horizontal pipe	1.0	0.65
UBB	1.0	0.75

RAFT allows also to compute linear hydrodynamic coefficients using a potential flow approach, instead or in addition to the use of the Morison equation, using the solver **HAMS** [126]. The meshing operation of the submerged members of the substructure is handled internally and pass on to the solver to get the substructure's hydrodynamic coefficients database used for computing the added mass and damping but also the wave excitation force. In addition, this can also be useful in the pre-processing steps for building a similar numerical model to be used in **TD** simulations for example with **OpenFAST**. The mass and inertial details of the **FOWT** system as well as the hydrostatics and hydrodynamic coefficients of the substructure can be passed on to perform more detailed or time varying analysis. After the linearization process, the complex amplitude of the system's response is determined by solving the transfer function of the linear matrix equation 3.2, the so-called **RAO** of the system, iteratively until convergence. Finally, for a given mean wind speed and wave spectrum parameters, the **FOWT**'s mean offset due to steady loads and its response in the **FD** are computed. The maximum platform offset is then estimated by combining the mean state value with three times the standard deviation of the system's complex response spectrum:

$$X_{max} = \bar{X} + 3\sigma[\tilde{X}(\omega)]. \quad (3.8)$$

Similarly, key quantities of interest, such as the tower top nacelle acceleration and the tower base bending moment in the fore-aft direction, can be estimated from both the mean operational point and the maximum position of the **FOWT**. Again, the mean values are computed based on the system's operational point, while the maximum values are estimated from the complex response spectra corresponding to the quantities of interest. Information related to the mooring system is also assessed, including the tension in each mooring line for the mean operational point, complemented by evaluating the Jacobian matrix with respect to the system's degrees of freedom, to assess the mooring line tension dynamic amplitudes and estimate the maximum tension in each line. Different **DLCs** can be defined to include multiple wind and wave conditions, allowing for a comprehensive evaluation of the system's dynamic response under different environmental scenarios. This process is essential for assessing a given substructure design of the **GICON[®]-TLP**.

3.5. Optimization Process

As seen in the literature, evolutionary algorithms, particularly **GAs**, are commonly used in **FOWT** design optimization due to the complexity of the optimization problem. The main goal of the design optimization framework presented here is to reduce the cost due to the manufacturing of the **GICON[®]-TLP**. Depending on the numerical model chosen, this refers to the material mass, m , of either the **UBB** structure or the entire **GICON[®]-TLP** platform multiplied by each material unit cost. Several constraints are formulated to account for the results of the numerical analysis performed, such as limiting the stress in some components of the substructure or ensuring the dynamic performance of the **FOWT** system under different environmental conditions.

For a given design solution, represented by a set of design variables x , the constrained single-objective optimization problem can be expressed as:

$$\begin{aligned} &\text{minimize: } m(x), \\ &\text{subject to: } x_i^L \leq x_i \leq x_i^U \quad \forall i \in \llbracket 1; n_x \rrbracket, \\ &\quad \quad \quad g_j(x) \leq g_j^{lim} \quad \forall j \in \llbracket 1; n_g \rrbracket, \end{aligned} \tag{3.9}$$

where x^L and x^U denote the lower and upper limits of the design space and g_j is an inequality constraint with its associated limit g_j^{lim} . To numerically solve this problem, an efficient GA is specifically implemented and explained here. The optimization process is inspired by the CMNGA introduced and detailed in [127] and illustrated in Figure 3.8. This algorithm was developed to address some of the main limitations of evolutionary algorithms and applied in FOWT substructure design optimization. This specific GA is capable of handling multi-modal objective functions using niching techniques while also reducing the number of problem evaluations. Unlike traditional evolutionary algorithms, where the population size remains constant, the population in this approach expands and evolves over generations, exploring the design space through fitness scaling and an addition operation.

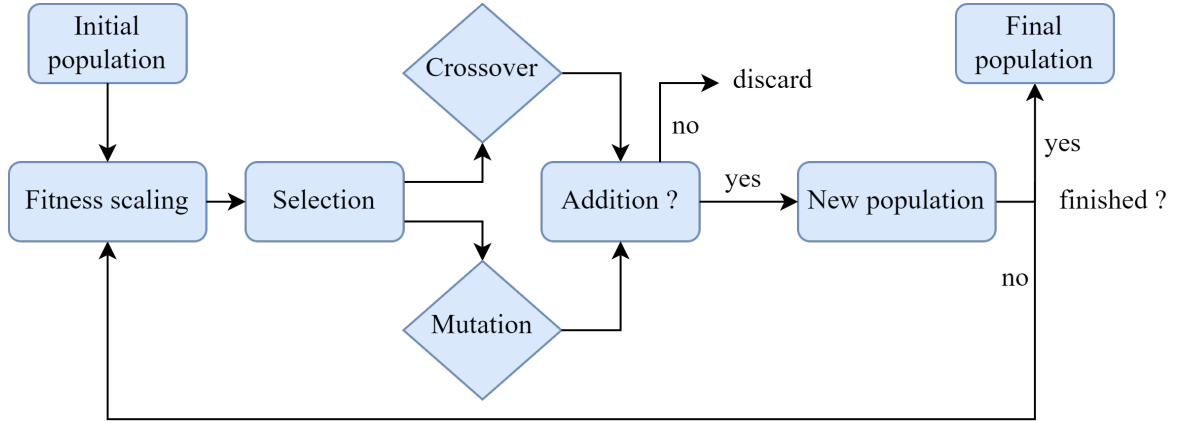


Figure 3.8. Structure of the CMNGA implemented for the optimization process.

At the beginning of the optimization process, the initial population is generated and consist of n_{min} individuals. Typically, when using GAs, this initial population is drawn using a random sample within the design space. However, this method may not be ideal, as the performance of the optimization heavily depends on how well the population represents the entire range of possible solutions. In this framework, it is crucial that the initial population efficiently covers the search space to improve the algorithm's performance. To address this, different sampling methods are implemented: uniform, random approach, LHS, and Sobol sequences. Figure 3.9 illustrates the initial population of 100 individuals in a two-dimensional space, generated by a each of these methods.

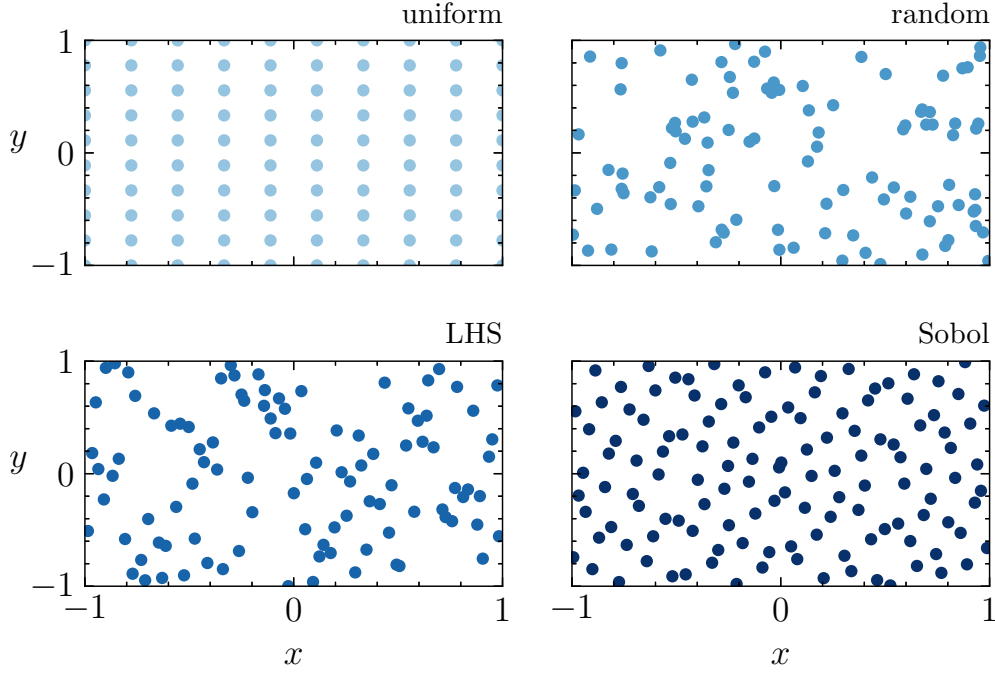


Figure 3.9. Comparison of uniform, random, LHS, and Sobol sequence sampling methods for the generation of the initial population for 100 individuals.

The LHS method is designed to efficiently explore the solution space by dividing it into equally probable intervals, ensuring that each of these interval is sampled exactly once without replacement. This allows to avoid overlap between selected points and reduces the chances of obtaining redundant or unrepresentative samples. The LHS method is widely applied not only in optimization studies but also in different topics such as uncertainty analysis. Sobol sequences, by contrast, are used to generate uniformly distributed samples across a multi-dimensional space. Unlike purely random sampling, this methods aims to minimize gaps and clusters, enhancing coverage of the design space. The two last methods mentioned are particularly suitable for high-dimensional optimization problems, where uniform sampling is essential for faster convergence and more reliable results [128].

In order to rank all individuals within the population the fitness of each individual is evaluated based on their objective and constraint values. In the CMNGA, all significant local optima identified during the process are treated equitably by using a distance-weighted scaling operation that adjusts the fitness distribution of the current population. This operation is used here alongside an efficient constraint handling technique that is applied before the scaling process in order to solve the optimization problem effectively. A common approach when using GAs is the application of penalty functions which requires a clear definition and relevant tuning of their parameters, often resulting in problem-dependent penalty functions. Here, the constraint handling technique developed in [129] is applied, which allows infeasible solutions, those for which at least one constraint is violated, to be compared only based on their total constraint violation.

For a given constraint the violation is simply computed as:

$$v_j(x) = \begin{cases} g_j(x) - g_j^{lim} & \text{if } g_j(x) \geq g_j^{lim}, \\ 0 & \text{otherwise,} \end{cases} \quad (3.10)$$

and the penalty term is computed considering a quadratic form of the total constraint violations as:

$$p(x) = n_v \sum_j \alpha_j \left(\frac{v_j(x)}{v_j^{max}} \right)^2, \quad (3.11)$$

where n_v is the total number of violated constraint for a given individual, α_j a given coefficient and v_j^{max} the maximum violation across the current population for a given constraint. Finally, as the objective of the optimization is to minimize the mass of the **GICON®-TLP** or the **UBB**, the fitness of a given individual is defined as:

$$f(x) = \begin{cases} -m(x) & \text{if feasible,} \\ -(m^{max} + p(x)) & \text{otherwise,} \end{cases} \quad (3.12)$$

where m^{max} is the maximum mass across all design solutions within the feasible population, those for which all constraints are respected. This form of the penalty function provides a clear comparison between feasible and infeasible solutions, allowing the algorithm to effectively handle constraints. The objective is minimized by linearly scaling the fitness values between their maximum and minimum, assigning the least fit individual a value of 0 and the fittest individual a value of 1, as it is commonly done using **GAs**.

A special distance-weighted scaling operation is then performed in the **CMNGA** to account for local optima within the growing population. The process allows each local optimum identified within the population to get an equal scaled fitness value of 1 in order to be treated equally. For this purpose, a simple proximity-based criterion is used where an individual is considered a local optimum if it is fitter than all of its nearest neighbors within a specified distance range denoted d_{min} . During the whole optimization process, a distance matrix is created and updated each generation to keep track of the distance between each and every individuals within the population. The distance between two given individuals, a and b , is defined as the Euclidean distance of their design variable vectors, normalized by the distance between the upper and lower bounds of the design space, as:

$$D_{a,b} = \frac{\sqrt{\sum_i (x_i^a - x_i^b)^2}}{\sqrt{\sum_i (x_i^l - x_i^u)^2}}. \quad (3.13)$$

The scaling operation, along with the previously defined constraint-handling technique, is illustrated in Figure 3.10, demonstrating the scaling process applied to a simple constrained multimodal function being minimized with its associated fitnesses, while highlighting its two local optima. Once n_k local optima have been identified, the fitness of the entire population is scaled to the fitness of each optima, resulting in n_k fitness values $f_k(x)$ for each individual. A first scaling is applied to linearly map the population's fitness to the fitness of a given optimum, while ensuring that the median of all scaled values is 0.5. These fitnesses are then summed and weighted according to the individual's distance to each local optimum, leading to the total population scaled fitness f_s , as in [127]:

$$f_s(x) = \frac{\sum_k f_k(x)/D_{x,x_k}}{\sum_k 1/D_{x,x_k}}. \quad (3.14)$$

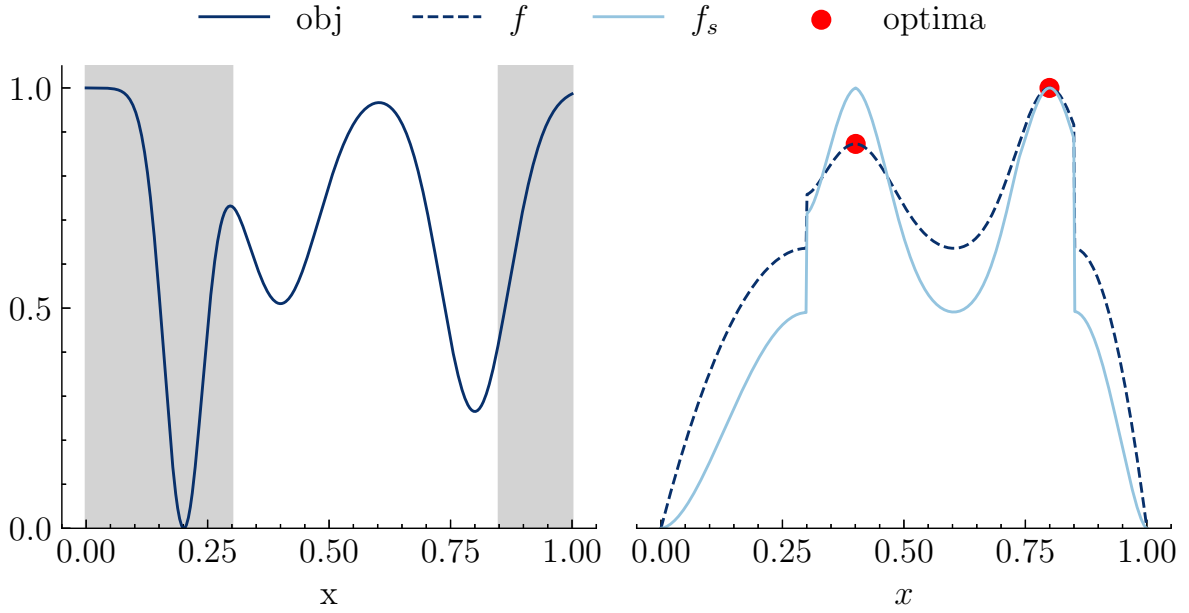


Figure 3.10. Illustration of the fitness scaling operation applied on a constrained (gray area) multimodal function being minimized.

To make the initial population evolved, new individuals are generated using genetic operators such as crossover and mutation operations before being potentially added to the existing population. Namely, the **SBC** and a polynomial mutation operation, originally introduced in [130, 131], are chosen for their efficiency and implemented for the present efficient **GA**. This crossover operation is widely used in many different studies for solving real value optimization problems and replicates the single-point crossover which is typically involved when binary-coded representation of the continuous design variables is done.

As a crossover operation it generates offspring by creating a blend of parent solutions based on a probability distribution which is defined by spread factor β , as in [130]:

$$\beta = \begin{cases} (2u)^{\frac{1}{\eta_c+1}} & \text{if } u \leq 0.5, \\ \left(\frac{1}{2(1-u)}\right)^{\frac{1}{\eta_c+1}} & \text{otherwise,} \end{cases} \quad (3.15)$$

where u is a random number between 0 and 1. This spread factor is controlled by a distribution index parameter η_c , which determines how closely the offspring are to their parents. For given set of two selected parent's design variables, x^{p1} and x^{p2} , two new sets of design variables x^{o1} and x^{o2} are computed, as in [130]:

$$\begin{cases} x^{o1} = \frac{(1+\beta)x^{p1} + (1-\beta)x^{p2}}{2}, \\ x^{o2} = \frac{(1-\beta)x^{p1} + (1+\beta)x^{p2}}{2}. \end{cases} \quad (3.16)$$

The selection process of the CMNGA for the parents of the crossover operation combines a fitness and distance proportionate approach to account for the objective and constraints but also the proximity of individuals. The first parent is selected from the current population using a fitness-proportionate roulette wheel selection method, where each individual is assigned a probability of selection proportional to its fitness, favoring better solutions. The second parent is also chosen using roulette wheel selection, but this time with probabilities inversely proportional to the distance of individuals from the first parent, using the distance defined in equation 3.13. A mating crowd is thus formed for the first parent, consisting of individuals that are more likely to be within its neighborhood, and the fittest individual of the crowd is then selected as the second parent. This method tends to select parents that are both fit and located in the same region of the design space.

The mutation scheme follows a more traditional process and uses polynomial probability distribution to perturb a given individual's design variables while ensuring that the mutation respects the design space boundaries. For given selected set of design variables, x^p , the mutated offspring's new set of design variables x^m is compute, as in [131]:

$$x^m = \begin{cases} x^p + \delta(x^p - x^l) & \text{if } u \leq 0.5, \\ x^p + \delta(x^u - x^p) & \text{otherwise,} \end{cases} \quad (3.17)$$

with:

$$\delta = \begin{cases} (2u)^{\frac{1}{\eta_m+1}} - 1 & \text{if } u \leq 0.5, \\ 1 - (2(1-u))^{\frac{1}{\eta_m+1}} & \text{otherwise,} \end{cases} \quad (3.18)$$

where η_m is another distribution index which determines the probability distribution of the mutation's magnitude.

The selection of individuals for mutation is done randomly and each variable is assigned a mutation probability of $1/n$ so that on an average one variable is disturbed. The [SBC](#) and mutation operations implemented are both illustrated in figure 3.11 where the distribution of offspring generated for growing values of their respective distribution indices (from dark to light blue). A low distribution index for the crossover operation results in offspring that are more diverse, while a higher value leads to offspring that are closer to their parents. Similarly for mutations, high values of distribution index will lead to smaller perturbations and a finer local search while lower index allows for larger mutations and promotes more exploration. Parametric studies performed in [131] that the distribution index for the polynomial mutation to perform the best lies in values between 100 and 150, and values for the crossover index are often chosen between 10, 50 for performance on multi-modal function [132].

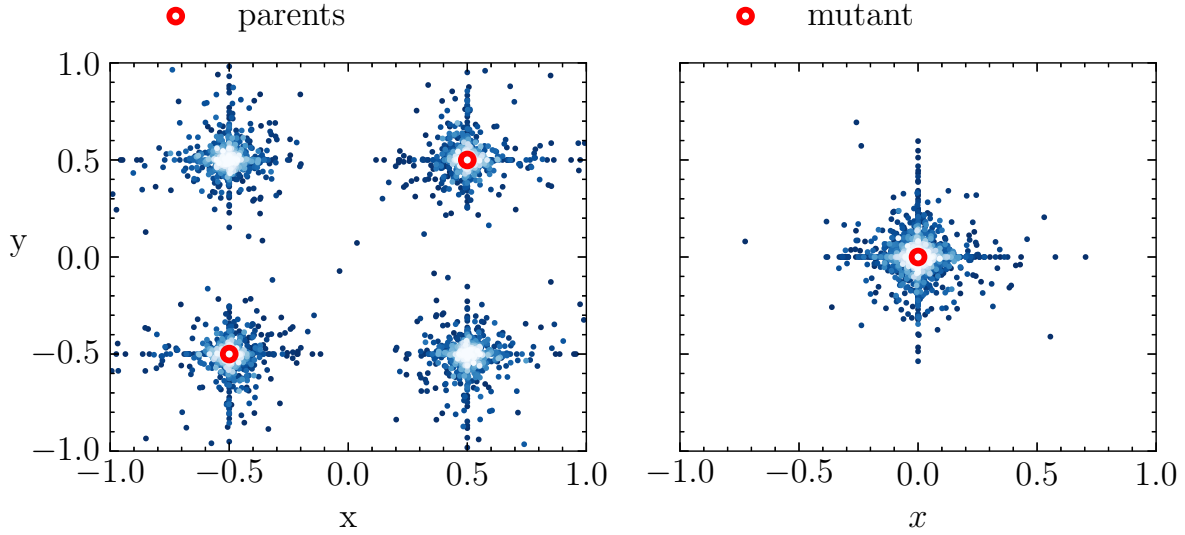


Figure 3.11. Offspring generated by the [SBC](#) (left) and mutation (right) operations, for growing values of the distribution index (from dark to light blue).

After new offspring are generated, the addition operation determines whether they should be added to the current population by ensuring they are not too similar to existing individuals, while still remaining close to fit ones. This check is performed before evaluating their fitness values, avoiding the computational cost of solving the optimization problem for individuals that will not be added. This approach is particularly beneficial in our case, as evaluating the objective and constraint functions requires significant computational resources to run the numerical models detailed. It also ensures that the population evolves towards fitter regions of the design space, resulting in lower population density in less fit areas. Figure 3.12 illustrates the addition operation for a two-dimensional objective function being minimized highlighting the current population, the generated offspring (using the previously defined operators) and whether or not they are added to the population based on the following distance criteria preventing unnecessary fitness evaluations.

In [127], the proximity constraint is fitness-related and compares the distance between a given new offspring and the closest individual in the population, to a threshold that is computed based on this particular individual's fitness. For a given new offspring and its associated design variables x_o and its closest neighbor x_n , the distance threshold compared to their distance is defined as:

$$(d_1 - d_0)f_s(x_n)^2 + d_0 \leq D_{o,n}, \quad (3.19)$$

where, d_0 and d_1 are two distance parameters which represent the minimum distance that a new individual must maintain from the best and worst individuals in the current population to be accepted. Specifically, the function sets a distance threshold of d_0 around the fittest individual and d_1 around the least fit individual. An adjustment to this threshold is proposed, enabling it to evolve linearly or exponentially with the growing population size or across generations. This helps to adapt to the evolving objectives of the algorithm during the optimization process and help prevent premature convergence. Finally, the optimization process continues until the algorithm reaches a maximum population size n_{max} or a predefined number of generations, or any other convergence criteria, typically based on the optimum solution's improvement. By the end of the optimization process, the population has converged towards fitter regions of the design space and a significantly higher concentration around the identified local optima and the global optimum, which represents the solution to the optimization problem.

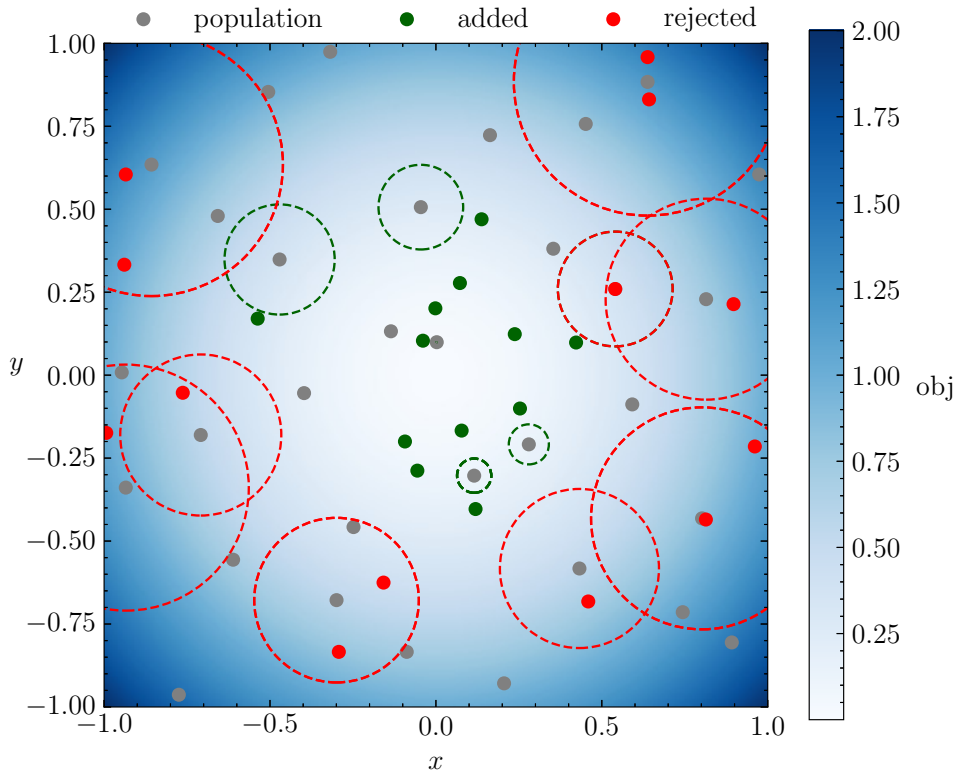


Figure 3.12. Illustration of the addition operation.

3.6. Implementation

The design optimization framework presented here is implemented using Python, which is widely used due to its extensive ecosystem of open-source libraries and makes the code concise and easy to share. The core of the implementation lies in linking the optimization process with the two numerical analyses previously detailed. The final structure of the framework is shown in Figure 3.13 and illustrates the interaction between these two main components: the efficient GA and the two numerical models. It also highlights the evolution of the algorithm's population during the optimization process, including the initial population and the final one, which contains the identified local optima.

At the start of the process, inputs are provided to specify all necessary parameters for both the optimization and the numerical analyses. An input file, typically in .json or .yaml format, is read into a dictionary, which is useful in Python for defining keyword-based parameters. The optimization parameters include settings critical for the GA's performance, such as the initial and maximum population sizes, as well as the crossover and mutation operator indices. Additional parameters for identifying local optima and executing the addition operation are also specified at this stage. The mathematical optimization problem is defined by specifying the design variables, derived from the parametrization of the structure to be optimized, along with their respective boundaries, as well as the various constraints and their corresponding limits, which are provided as inputs.

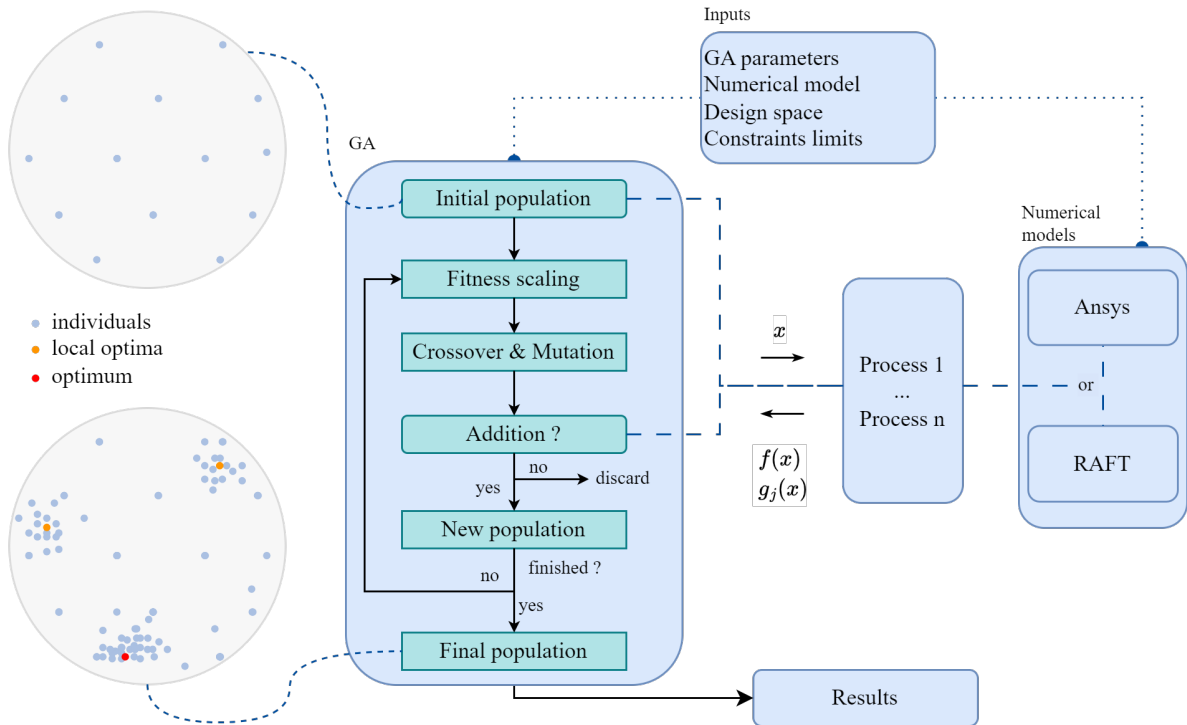


Figure 3.13. Structure of the design optimization framework implemented coupling the efficient GA with the two numerical models previously detailed.

The choice of numerical model shapes the optimization problem and influences the design parametrization and how objectives and constraints are computed during the evaluation of the individuals. For instance, when the structural model is selected, the parametrization and design space focus on the cylindrical **UBB**, exploring variables such as cover thicknesses, diameters, and structure length. In contrast, the **FD** dynamic model considers the entire **GICON®-TLP** substructure design, which is more complex and may involve additional design variables and constraints. The numerical models also require inputs such as the mooring force at the base of the UBB or the Design Load Cases (**DLCs**) for which the **FOWT** system's behavior must be assessed and optimized. Once all inputs are defined, the optimization process begins, following the steps outlined previously.

For analyzing a given **UBB** design, the **FEA** tool Ansys is used, with simulations performed via **APDL** commands. This scripting language controls the Ansys Mechanical solver, enabling geometry setup, meshing of complex structures, and launching the structural analysis. Python allows for integration via PyAnsys [133], a collection of packages that facilitate the use of Ansys products. **APDL** commands can be executed directly through Python, or command files can be launched. For each individual design being assessed, an entire script is generated, including geometry for meshing. Postprocessing is similarly automated, extracting key outputs such as maximum stress and total mass for a given design. The dynamic analysis is performed using the **RAFT** code, which evaluates both static properties and dynamic responses in the **FD**. Written in Python and open-source, **RAFT** is easily integrated into the optimization framework. The entire **FOWT** system, including the turbine, RNA, tower, mooring system, and substructure, is defined in **RAFT**, with the set of **DLCs** and other parameters provided in the input file for the analysis. Since the optimization focuses on the floating platform design, a base model containing all other necessary parameters is used and modified for each new design of the **GICON®-TLP** to assess its performance.

Given that the optimization process is population-based and computationally intensive due to the numerical analyses involved, the framework makes use of multiprocessing to evaluate a given number of individuals simultaneously, distributing the workload across several processes. This is especially effective because each design's evaluation is independent of the others, making it highly suitable for parallel execution. This significantly accelerates the evaluation of multiple designs during the initialization of the population and after the addition operation, when the objective and constraint values of new offspring are computed.

The optimization continues until either the maximum population size or the predefined number of generations is reached. Optionally, a convergence criterion can be set, allowing the process to terminate early if the population shows no significant improvement over several generations. At the end of the optimization, the framework outputs the final population along with several key results, including the objective and constraint values for the identified optima and the entire population. These outputs provide not only the optimal design but also insights into the design space, identifying regions with densely packed solutions that may indicate areas of interest for further exploration.

3.7. Validation

To validate the correct implementation of the implemented design optimization framework, both the numerical models and the optimization process are tested and verified. This ensures that everything functions properly before applying the framework and builds confidence in its results. The first numerical analysis implemented in the framework is the structural model of the [UBB](#), performed using the [FEA](#) tool, Ansys. Ansys is widely used and trusted in various engineering fields for solving complex structural problems, having undergone extensive validation, which ensures confidence in its results. The development of the model follows the work detailed in [66], where the [UBB](#) design is introduced, analyzed, and validated using Ansys to assess its structural integrity for a given geometry. The structure's mesh is carefully chosen, as in the original study, to ensure high-quality meshing, and a convergence study is performed to ensure the stress results in the structure are consistent. Results for different geometries have been obtained and verified, confirming coherence with those from previous studies. Even though the structural analysis performed is relatively simple, it validates the structural design of this multi-use component, its integration into the [GICON[®]-TLP](#), and its potential use in other [FOWT](#) substructures.

The [RAFT](#) tool used for the dynamic analysis of the entire [FOWT](#) system is validated in [123] by comparing its results with established reference models, including the OC4 DeepCwind and VolturnUS-S semi-submersibles. These validations benchmarked [RAFT](#) against higher-fidelity tools, such as OpenFAST, showing good agreement while maintaining computational efficiency. This makes [RAFT](#) ideal for quickly evaluating various substructure designs under different environmental conditions with a high degree of accuracy. Additionally, [RAFT](#) has demonstrated its ability to accurately compute rotor aerodynamic coefficients for the [IEA](#) 15 MW reference turbine [134], which is also used in this thesis. The validation of the [GICON[®]-TLP](#) model, using this turbine, was conducted through static comparisons with numerical models from previous studies, including designs for similar or smaller offshore turbines in [65, 67, 120], as well as earlier work performed at [LWET](#). Table 3.3 presents the natural frequencies of the [GICON[®]-TLP](#) for a similar design and computed using the [RAFT](#) FD dynamic model. These frequencies as well as the mass distributions and other properties fall within an acceptable range of deviation when compared to [120], considering slight differences in platform geometry and the turbine used. They are also close to the natural frequencies of other [TLPs](#) platforms reported in other studies, such as [62, 105], and to the general frequencies for such system given in different the standards.

Table 3.3. Natural frequencies of the [GICON[®]-TLP](#) computed using [RAFT](#).

	surge	sway	heave	roll	pitch	yaw
Natural frequency (in Hz)	0.0228	0.0217	0.4057	0.1802	0.1801	0.0251

To validate the efficiency of the implemented GA, the optimization process is tested on several benchmark problems, as it is commonly done when developing optimization tools. The Three-Hump Camel function (three distinct local optima) and the Schwefel function (many local optima) are used to assess the algorithm's ability to identify local optima, while the Hartmann and Sphere functions evaluate its performance for multidimensional design space. The constrained Gomez-Levy function and a classical welded beam design optimization problem are also included to assess challenges related to local optima identification with constraint handling, and practical design optimization scenarios. These optimization test problems are widely referenced in the literature, as seen in [127, 131, 132, 135], and their definitions follow those detailed in [129, 136, 137], which are given in appendix, see Section B.

Due to the inherent randomness of GAs, each test problem is run 10 times to collect statistical results from multiple optimization runs and properly assess the results and efficiency of the implemented GA. For each run, the initial population is generated using Sobol sequences (using the same seed for consistency), with sizes ranging from 50 to 100 individuals, depending on the dimensionality of the problem. In each generation, 20 individuals are generated through crossover and 10 through mutation, using fixed distribution indices of $\eta_c = 50$ and $\eta_m = 100$, respectively. The threshold distances are set to $d_0 = 0.1$ and $d_1 = 1e - 4$, and the minimum distance d_{min} for local optima identification is set to 0.1, except for the Sphere function in high dimension, where a value of 0.25 is applied. The maximum population size is capped, resulting in a maximum of 5000 problem evaluations for all test functions, which is significantly lower or similar to the figures commonly reported in the literature for other evolutionary algorithms, including GAs. The Gomez-Levy function is illustrated in Figure 3.14, highlighting its multimodality and the constrained regions, in gray, of the design space.

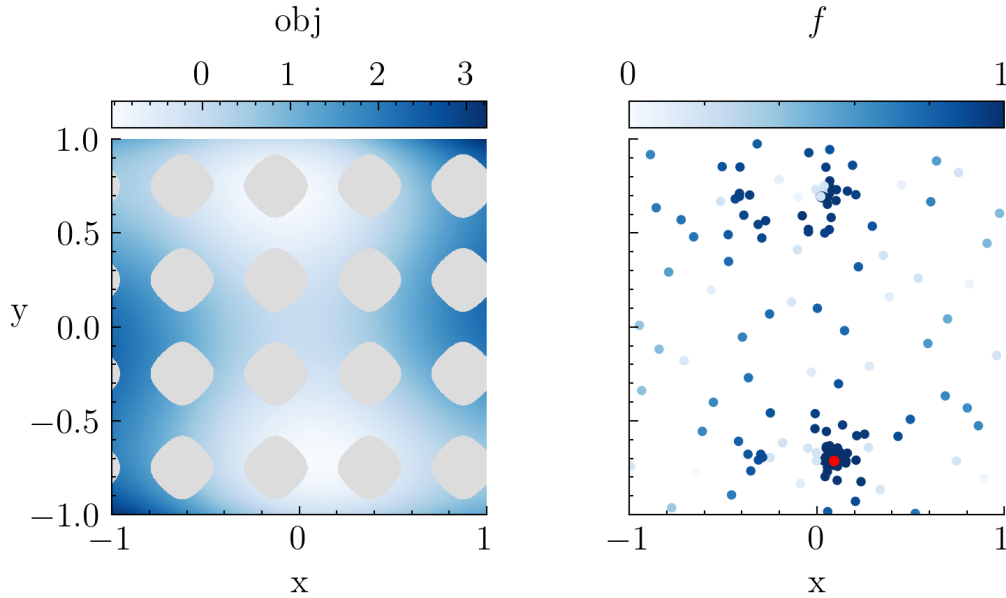


Figure 3.14. The Gomez-Levy function and distribution of the final population.

The statistical results collected from the 10 optimization runs include the minimum, maximum, mean, and standard deviation of the design variables, as well as the corresponding objective and constraint values for the global optimal solution obtained. Across all test problems, except for the welded beam design problem, the implemented GA exhibited consistent performance, with small standard deviations and minimal variation between runs. This was expected, as the welded beam design is originally a multi-objective optimization problem with a wide design space and complex constraints, for which the implemented constraint handling techniques can only adapt to a certain extent. This led to near optimal solutions in some runs, highlighting the importance of repeated optimization runs. However, for all test problems and all optimization runs, the algorithm successfully found an optimal solution relatively close to the one reported in the literature, along with additional local optima identified during the process. For constrained problems, the GA consistently satisfied constraints while minimizing the objective, effectively ignoring optima in infeasible regions (if any) of the design space. The results for the Gomez-Levy function and the typical welded beam design optimization problem are emphasized here as they involve multimodality, multidimensionality, and constraints related challenges similar to those in optimizing the structure of the GICON[®]-TLP and its components in the following chapter. Detailed validation results for each test function can be found in the appendix, see Section B. Figure 3.15 shows the evolution of the objective and constraint values for the global minimum identified during the optimization of the welded beam design problem.

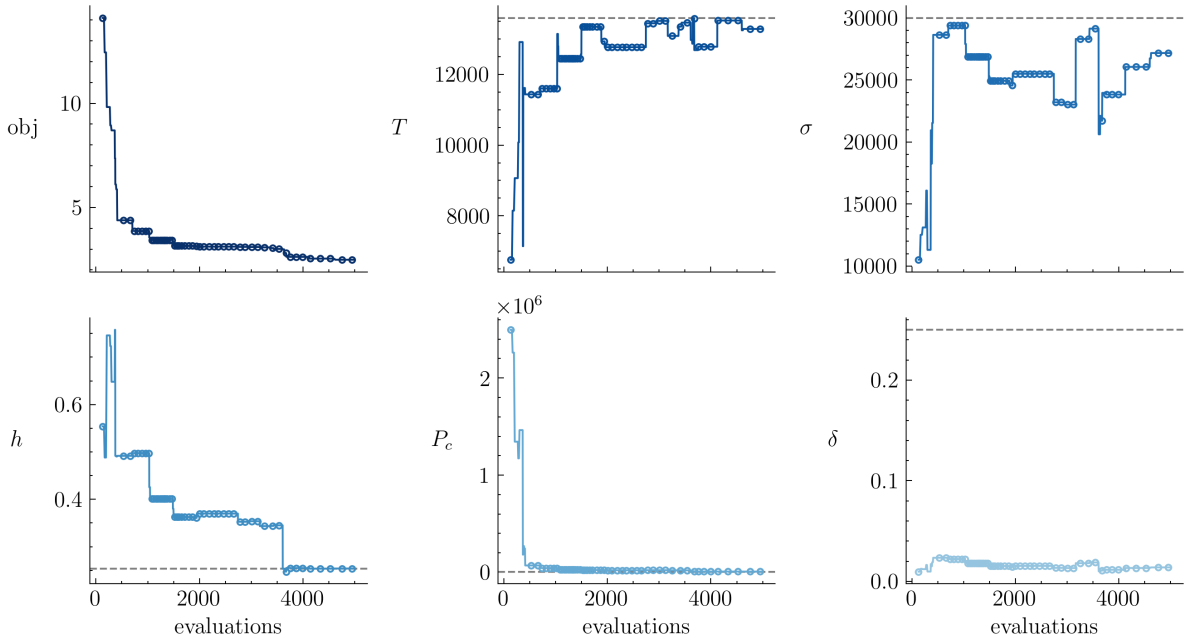


Figure 3.15. Objective and constraints evolution for the welded beam design optimization problem.

Additionally, Figure 3.16 illustrates the pairwise distribution of design variables in the final population at the end of the optimization. As expected, the final population density is concentrated in the fittest regions of the design space, where the objective is minimized, and constraints are satisfied. The GA also evaluated designs near local optima, demonstrating its ability to navigate different constraints effectively while identifying promising regions of the design space. Overall, these validation results confirm the effectiveness and robustness of the implemented optimization process, demonstrating its capability to identify multiple local optima, minimize objectives, and respect constraints across typical design optimization problems.

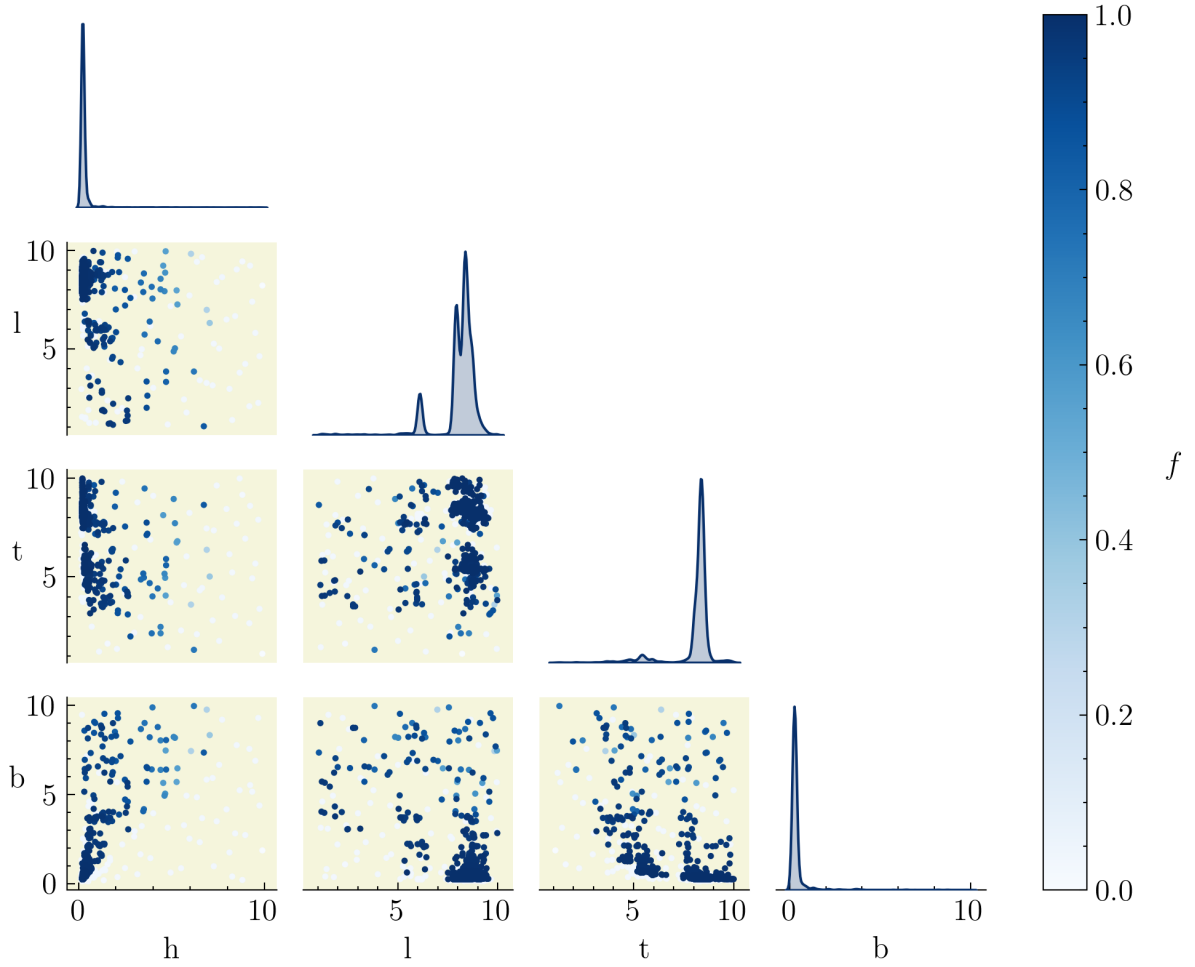


Figure 3.16. Pairwise distribution of the final population's design variables for the welded beam design optimization problem.

Design Optimization of the GICON[®]-TLP

4

This chapter presents the application of the previously detailed optimization framework for the design of the GICON[®]-TLP and its multi-use component, the UBB. The objective is to evaluate the framework's performance in addressing a typical FOWT substructure design optimization problem and to derive an optimized design for this specific substructure and its components. The chapter begins by outlining the design methodology used in this case study and details the application of the optimization framework. Two distinct optimization studies are conducted and presented. The first study focuses exclusively on the structural design of the UBB, while the second adopts a system-level approach, optimizing the entire GICON[®]-TLP substructure, taking into account the dynamic behavior of the FOWT system. For each analysis, key inputs are provided, including the parameterization and formulation of the optimization problem. Additionally, the optimization process parameters and results are presented. The chapter concludes by discussing the final optimized designs for both the UBB and the GICON[®]-TLP, along with an evaluation of the optimization framework's overall efficiency.

4.1. Design Approach

The objective of this design optimization study case is to minimize the total cost associated with the manufacturing of the GICON[®]-TLP and to demonstrate the application of the proposed optimization framework. The design level targeted here is consistent with the precision of the numerical analyses implemented and used in the framework. The aim is to conduct a simplified yet reliable analysis focusing on the early design phase of both the GICON[®]-TLP and the UBB, where key decisions regarding the overall geometry of the structure and its design are made. While more detailed models and analyses will be necessary in later design stages, they are generally not suitable for early design optimization work due to computational costs which grows with the models' accuracy. More advanced analysis would require long dynamic analysis and more complex load cases, which are beyond the scope of the current study case.

The first part of this study focuses on the structural design of the UBB, refining its initial concept as a multi-use component for the GICON[®]-TLP presented in [66]. It involves a basic structural analysis and geometrical optimization to minimize the UBB's mass while ensuring it meets strength and buoyancy requirements. Although this step does not represent the entire floating system and its complex interactions, it results in a general optimized design that can fit the GICON[®]-TLP. This allows for a comparison with the old typical structure of this particular buoyancy body and assesses the cost reductions possible through the use of multi-use components and the application of this design optimization framework.

The second study addresses the entire floating substructure design of GICON®-TLP. A frequency-domain dynamic model is used to account for the full FOWT system, focusing on optimizing the platform's overall geometry as well as the dimensions and position of the UBB. This analysis is conducted for a reference multi-MW OWT under various load cases, with the goal of reducing the overall mass and so the manufacturing costs, while ensuring the dynamic response remains within acceptable limits. Although the two optimization studies are separate and not directly linked, they offer valuable insights into the optimized designs of both the UBB and the GICON®-TLP. These results provide a good overview of trends in reducing system costs and highlight the potential for future development. Additionally, this process serves as a study case to assess the effectiveness of the optimization framework in the early-phase design of FOWT substructures.

4.2. Structural Optimization of the Universal Buoyancy Body

4.2.1. Design Parametrization

First, a set of design variables describing the cylindrical geometry of the UBB must be defined to parametrize the structure. This particular buoyancy body has a simple design, inspired by wind turbine towers and monopile structures, consisting mainly of two different pipes and upper and lower covers. Due to the symmetrical nature of the UBB design, only one out of the four components in the GICON®-TLP structure is considered, and only half of the geometry is parametrized, as shown in Figure 4.1, where the parameterization of the design is illustrated in sectional view. For this optimization work, the design variables considered are continuous real values and defined as follows: l is the cylindrical body's length (from the roots of both covers), d_0 and d_1 represent the diameters of the concentric inner and outer pipes that are used for manufacturing the UBB, while t_0 and t_1 denote the inner and outer thicknesses of these pipes. For the sandwich type covers, the concrete and steel parts are parametrized by two different thicknesses t_c and t_s , respectively. Structurally, it can be advantageous for the concrete part of the covers to increase towards the inner pipe of the UBB as it presents a sensible hot spot for stress concentration, so an expansion coefficient c_{exp} is considered to account for this feature. Since both the upper and lower covers can be either flat or conical, an angle α is introduced and represents the covers' angle as shown in Figure 4.1. In terms of manufacturing this cylindrical conical shape can be considered as cast techniques exist to build such structure. To simplify the optimization problem, and also the manufacturing process, the design variables for the upper and lower covers are considered identical, allowing for an easier serial production of multiple components. Finally, the complete set of design variables considered in this study is defined as:

$$x = [l, d_0, d_1, t_0, t_1, \alpha, c_{exp}, t_c, t_s]. \quad (4.1)$$

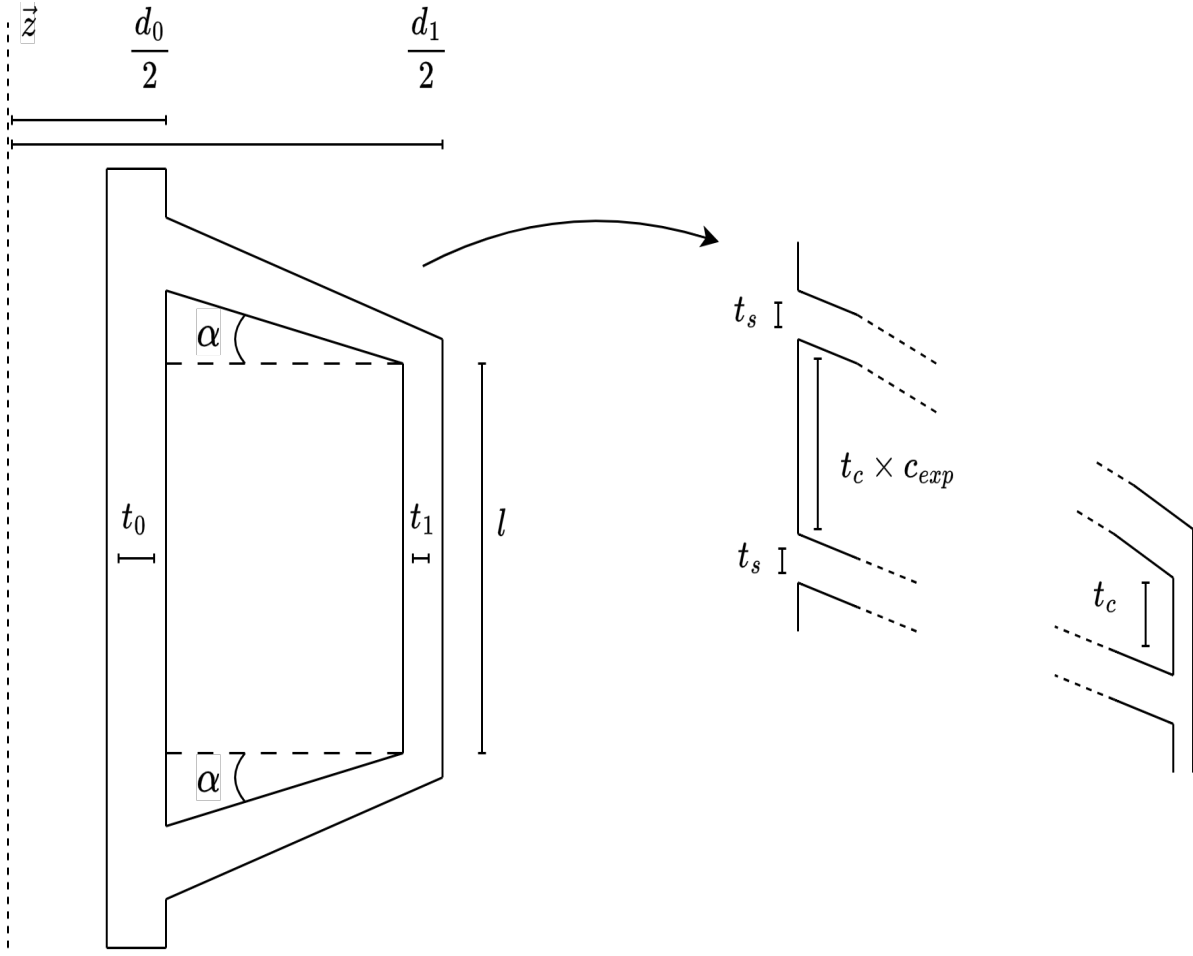


Figure 4.1. Design parametrization of the UBB and its covers.

4.2.2. Problem formulation

The objective of the considered design optimization problem is to minimize the mass of a single UBB while ensuring it meets both floatability and structural integrity requirements. The overall mass of the structure is calculated based on the volume of each material used and the material densities specified in Table 3.1. The two main materials required for the manufacturing of the UBB and its covers are steel and concrete. This selection is significant, as concrete is not only lighter than steel but also provides structural strength and is more cost-effective, directly impacting the mass minimization objective of this optimization. This material choice aligns with recent trends in FOWT substructure design, as more new concepts tend to incorporate concrete components in their structures. The design optimization of the UBB focuses on optimizing various geometric parameters, including the diameters and thicknesses of both the inner and outer pipes, as well as the thickness of the concrete and steel layers within the covers. As shown in the design parametrization, a total of 9 design variables are considered, creating a quite large design space that challenges the implemented GA.

The design of the pipes used in the manufacturing of the UBB is similar to, and adapted from, wind turbine tower and monopile designs. Therefore, the thick steel sheets used introduce manufacturing constraints that must be accounted for to limit the range of each design variable. For the inner pipe, typical diameters range from 2 m to 4 m, with thicknesses between 20 mm and 150 mm. The outer pipe has a diameter range of 10 m to 15 m, with thicknesses varying from 50 mm to 100 mm. The steel layers in the covers usually range from 10 mm to 50 mm, while the concrete layers have thicknesses between 150 mm and 500 mm. The overall length of the UBB is assumed to fall between 8 m and 15 m, aligning with the typical dimensions of buoyancy structures found in other FOWT substructure designs. Furthermore, the cover angles are limited to a maximum of 30° to prevent potential manufacturing challenges. The maximum allowable expansion coefficient for the concrete layer in the covers is restricted to 3.

In this study, the UBB is designed to integrate with the GICON®-TLP, supporting a typical multi-MW FOWT and providing a buoyancy force of 6 MN. A critical design constraint is that the maximum stress in the structure must not exceed the yield stress limit of steel of 300 MPa. This conservative limit is grounded in industry standards and relevant studies, ensuring the structure's integrity under standard operating conditions. As outlined in the previous chapter, the design loads considered include tendon rope loads and hydrostatic water pressure due to variations in water levels, both of which are essential for accurately modeling and evaluating a given UBB design. These loads were derived from a multi-body load simulation using FLEX5, conducted in accordance with recognized design standards [97] and the methodology employed in [66]. Consequently, the input for the structural analysis includes a maximum mooring force fixed at 10 MN, while the maximum wave height used for calculating the water pressure gradient on the structure's outer surface is set to 5 m. Finally, the constrained single-objective design optimization problem considered for the UBB is defined as follows:

$$\begin{aligned}
 &\text{minimize:} && m_{ubb}, \\
 &\text{subject to:} && l \in [8 ; 15] \text{ m}, \\
 & && d_0 \in [2 ; 4] \text{ m}, \\
 & && d_1 \in [10 ; 15] \text{ m}, \\
 & && t_0 \in [20 ; 150] \text{ mm}, \\
 & && t_1 \in [50 ; 100] \text{ mm}, \\
 & && \alpha \in [0 ; 30]^\circ, \\
 & && c_{exp} \in [1 ; 3], \\
 & && t_c \in [150 ; 500] \text{ mm}, \\
 & && t_s \in [10 ; 50] \text{ mm}, \\
 & && F_b \geq 6 \text{ MN}, \\
 & && \sigma \leq 300 \text{ MPa}.
 \end{aligned} \tag{4.2}$$

4.2.3. Results

The results in this section are obtained using the proposed design optimization framework, specifically with the efficient GA detailed previously. The UBB design optimization problem considered is run 10 times to obtain more robust optimization results for the final set of optimized design variables. The optimization parameters used here are similar to those applied in the validation process, with minor adjustments to account for the computational cost associated with the FEA simulations required at each evaluation. Indeed, the structural analysis requires a substantial computation time (approximately 50 seconds) each time the values of the objective function and constraints are calculated and verified. The optimization process begins with an initial population of 50 individuals generated using Sobol sequences allowing a broad understanding of the design space early in the process. For each generation, 20 new individuals are produced via crossover and 10 via mutation, with fixed distribution indices set at $\eta_c = 50$ and $\eta_m = 100$. The threshold distances are set to $d_0 = 0.1$ and $d_1 = 1e - 4$, and the minimum distance d_{min} for identifying local optima is set to 0.25.

Table 4.1. Optimization results for the UBB design optimization problem.

	min	max	mean	std
l	8.000	8.135	8.021	0.03
d_0	2.002	3.922	2.598	0.658
d_1	10.402	11.169	10.898	0.153
t_0	22	25	23.5	0.945
t_1	50	50	50	0.0
α	26.6	29.9	28.3	1.2
c_{exp}	1	1.05	1.03	0.01
t_c	155	366	214	43
t_s	11	19	13	2
m_{ubb}	328.499	336.877	331.803	2.8
F_b	7.186	6.133	6.405	0.345
σ	246.178	299.759	289.522	17.083

The different optimization runs generally produced similar results for the objective to minimize, with an average minimum objective value around 330 t. Some deviations are observed in certain design variables, such as the concrete thickness in the covers and the maximum stress in the structure of the optimized designs obtained. The final population showed a degree of diversity in design variables. For some variables, the optimal value is clearly identified, while for others, local optima values are equally represented. This is due to the randomness of the optimization process and the complex formulation of the problem, which includes a substantial number of design variables and constraints that challenge the optimization algorithm. Table 4.2 provides the optimized design variables of the UBB, along with the corresponding mass and constraint values, for the design with the minimum mass obtained.

Additionally, Figure 4.2 presents a 3D visual comparison between the optimized structure and its original version presented in [66], including a sectional view detailing the composition of the covers. The optimized UBB design features conical covers with angles approaching the upper limit of 30 °. These conical covers enhance buoyancy compared to flat covers of similar mass and contribute, to some extent, to reducing maximum stress in the structure. Moreover, extending the concrete layer toward the inner pipe helps mitigate stress, particularly in areas prone to stress concentration, which are critical to the design. The length of the optimized UBB, along with the diameters, pipe thicknesses, and concrete layer thickness in the covers, is near the lower bounds of the design space. This outcome aligns with the objective of minimizing the UBB's mass, which directly correlates with its volume and thus its dimensions. Indeed, the algorithm tends to favor slender designs with sufficient steel sheet thicknesses, which not only minimize mass but also help reduce stress within the structure.

Table 4.2. Optimized design of the UBB and associated cost.

l	d_0	d_1	t_0	t_1
8.012 m	2.032 m	12.496 m	23 mm	50 mm
α	c_{exp}	t_c	t_s	
29.23 °	1.05	272 mm	18 mm	
m_{ubb}	F_b	σ		
328.499 t	7.127 MN	299.759 MPa		

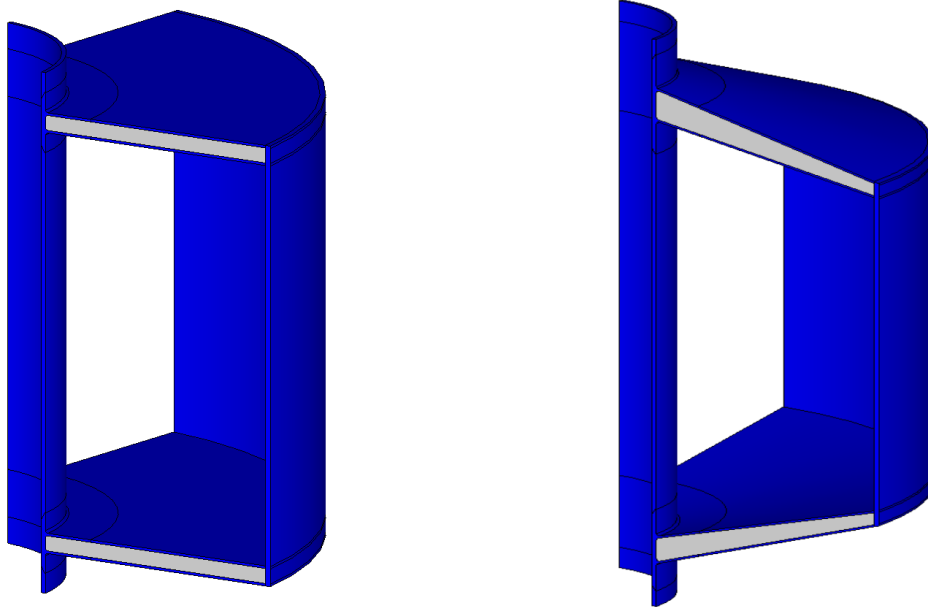


Figure 4.2. Original (left) and optimized (right) design of the UBB.

4.3. Dynamic Optimization of the GICON[®]-TLP

4.3.1. Design parametrization

Here again, a set of design variables is defined to parametrize the overall geometry of the GICON[®]-TLP. The latest design of this substructure consists of four UBBs arranged in a rectangular shape, connected by various pipes of specified lengths, diameters, and thicknesses. The goal here is to design this floater with integrated multi-use components, so the focus is on the geometric properties of these cylindrical buoyancy bodies and the overall width of the platform, as shown in Figure 4.3, where the design parameterization is illustrated in sectional view. For this optimization, the design variables are continuous real values and are defined as follows: l_{ubb} represents the UBB's length (including the covers), d_{ubb} its outer diameter, z_{ubb} the vertical position of its center from the MSL, and the width of the GICON[®]-TLP is denoted D . The complete set of design variables considered in this study is defined as follows:

$$x = [D, l_{ubb}, d_{ubb}, z_{ubb}]. \quad (4.3)$$

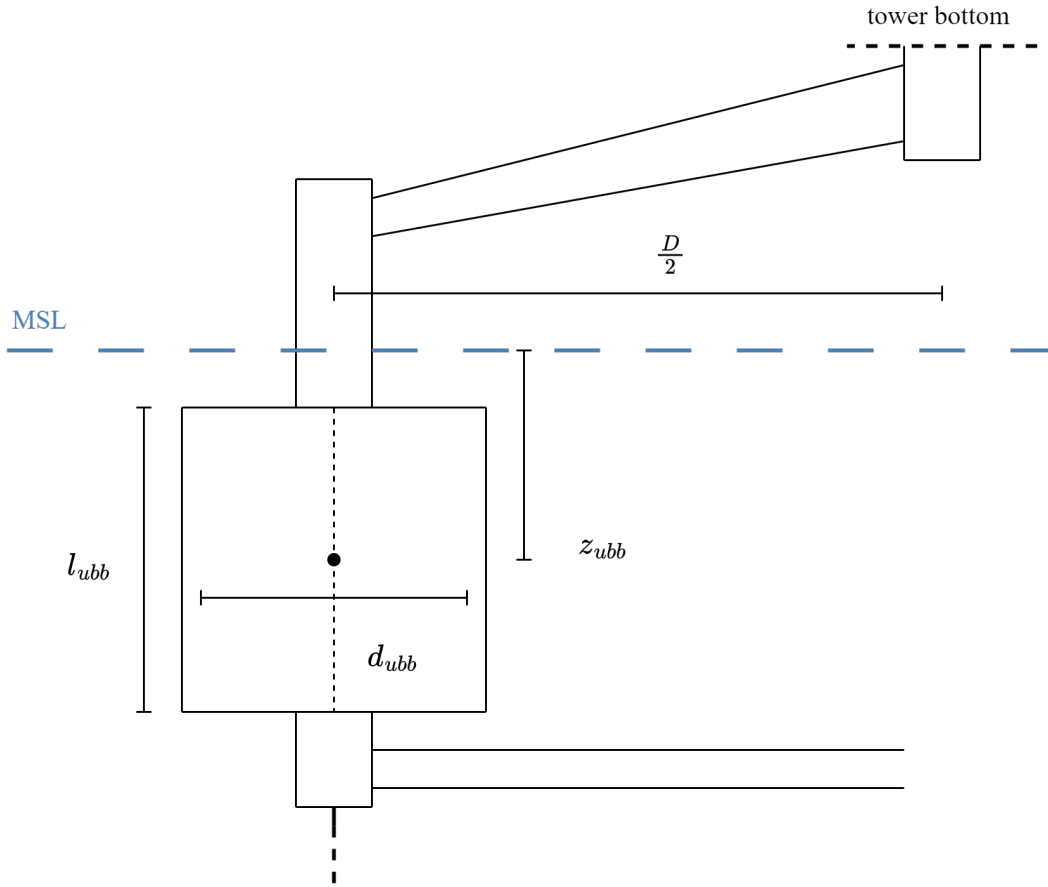


Figure 4.3. Design parametrization of the GICON[®]-TLP.

Since the UBB manufacturing process is conducted in series, and to simplify this study, all UBBs in the structure are assumed to have the same design. Their remaining design parameters, the thicknesses of the steel and concrete sections of the covers, are kept constant and derived from the previous optimization analysis. Modifying these parameters during this optimization process would have little effect on the dynamic analysis outcomes, given that no structural assessment is performed here. Although the previous analysis indicated benefits to using conical covers, the UBBs are modeled with flat covers here for simplicity. For the GICON[®]-TLP, the remaining design parameters are also fixed in this optimization. This includes the lengths and diameters of the upper node and all diagonal, vertical, and horizontal pipes in the substructure's design. The sheet thickness of all steel pipes (including those of the UBBs) is fixed and remains unchanged throughout the optimization process. Since the focus is on assessing the system's dynamics rather than its structural integrity, the impact of sheet thickness on system performance is minimal, so it is set to values typical of offshore structures. The positions of the upper node and the height of the horizontal pipe above the MSL are fixed. Additionally, the platform's draft, along with all geometric parameters related to the mooring system and wind turbine, remains constant and is detailed in the following section. This approach is chosen because modifying the draft or mooring system would significantly impact the analysis outcomes. To illustrate the applied design parameterization, Figure 4.4 shows different geometry obtained and their member-based modeling of the substructure using RAFT. A safety margin is included also to ensure that the top of the UBB doesn't come too close to the MSL or that its bottom doesn't collide with the horizontal pipe.

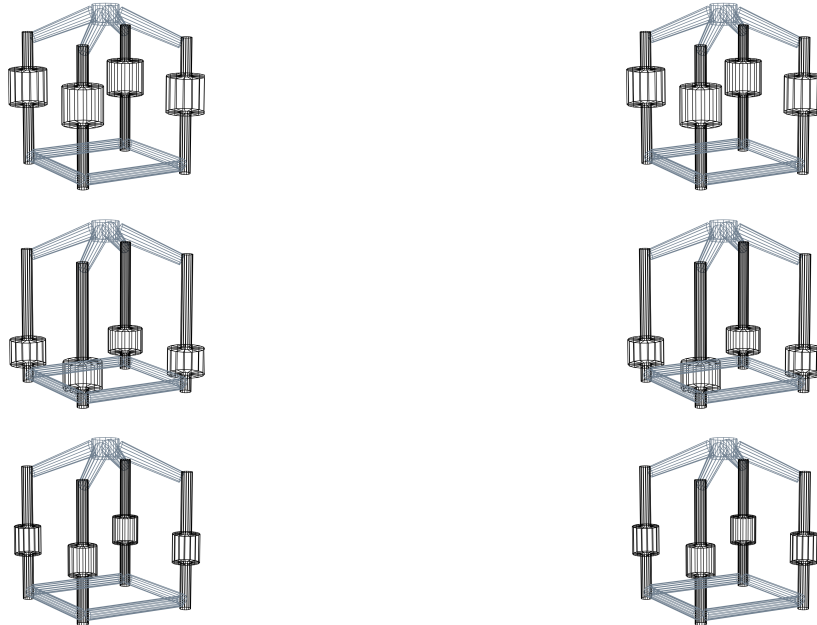


Figure 4.4. Illustration of the design parametrization of the GICON[®]-TLP.

4.3.2. Problem formulation

The objective of this design optimization problem is to minimize the total mass of the GICON[®]-TLP while ensuring its dynamic performance. In this study, the IEA 15 MW reference OWT is considered to form the FOWT system. This reference turbine, developed through collaboration between academia and industry, is initially presented and described in [134]. It is used here due to its extensive validation and widespread application in research, particularly in design studies on for next-generation FOWTs. This allows to derive an optimized design of the GICON[®]-TLP for large wind turbines, which are likely to become standard in the future, making it an ideal case for this study. The turbine model used here is the same as the one developed for the VoltturnUS semi-submersible, for which a RAFT model is publicly available in [122, 138]. The characteristics of the turbine used in this study, mainly the tower and RNA, remain unchanged and are given in Table 4.3. Additional information on this reference OWT can be found in its original report [134], as only basic information is provided here.

Table 4.3. Main characteristics of the IEA 15 MW used for the dynamic model.

Rotor diameter	240 m
Hub height	150 m
Tower length	120 m
RNA mass	991 t
Tower mass	1250 t
Power rating	15 MW
Rated wind speed	$10.59 \text{ m} \cdot \text{s}^{-1}$

To complete the FOWT system, a mooring system and its properties must be defined. The GICON[®]-TLP is designed to be towed to its installation site and stabilized using a simple mooring system combined with a self-lowering gravity anchor. For this purpose, four vertically aligned mooring lines are arranged in a square pattern, each connected to the bottom of a vertical pipe and to the anchor lying on the seabed at a depth of 200 m. However, the anchors themselves are not modeled in detail in RAFT, instead, the mooring lines are considered directly attached to the seabed. The characteristics of the mooring lines used in this study are identical for all lines and are provided in Table 4.4. The values used here are based on experience with the GICON[®]-TLP and similar TLP platforms, offering a reliable mean value for such systems, as detailed mooring information can be difficult to source.

Table 4.4. Mooring lines properties used for the dynamic model of the GICON[®]-TLP.

length	diameter	mass density	stiffness
160 m	155 mm	$125 \text{ kg} \cdot \text{m}^{-1}$	$2.25 \times 10^9 \text{ N}$

The FOWT system is evaluated in terms of dynamic responses under a reduced set of DLCs, each defined by stochastic sea states and steady winds, represented by a mean wind speed W_s and a JONSWAP wave spectrum with a significant wave height H_s and peak period T_p . While the environmental conditions in this study are not site-specific, they were selected based on experience values and previous design optimization studies, such as [110], to represent typical conditions that need to be assessed for the development of FOWT substructures according to standards. Additionally, the three representative environmental conditions chosen reflect typical values for mean wind speed and sea state encountered in Europe, as discussed in Section 1.2 Figure 4.5 illustrate the RAFT model of the GICON[®]-TLP and its different components and Figure 4.6 details the set of DLCs applied with the environmental conditions and the associated wave spectrum considered for this analysis. It is also worth noting that there is no wind-wave misalignment and that the forces are normal to the rotor plane.

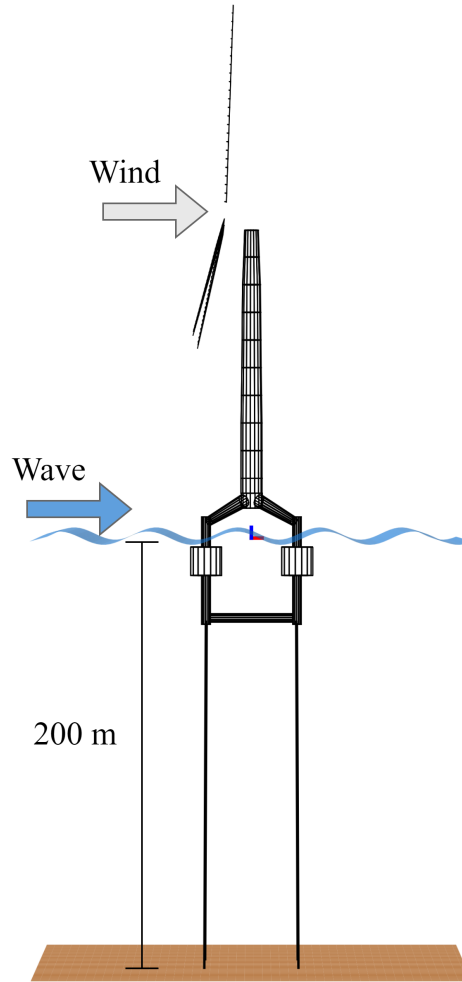


Figure 4.5. Illustration of the dynamic model for the GICON[®]-TLP.

In this design optimization study, the dynamic performance of the FOWT system is evaluated with constraints on specific aspects of the platform response and turbine behavior. The FD response is used to estimate the maximum platform offset, X_o , calculated as the norm of the surge and sway displacements of the system and constrained by a specified limit. Additionally, constraints are applied to the platform pitch, θ_p , and the nacelle acceleration, a_{rna} , at the top of the tower in the wind direction, ensuring these values remain within acceptable limits. Finally, the fore-aft bending moment at the tower base, M_{base} , is also considered, as it represents the stress that can be transferred to the substructure and is commonly limited in design.

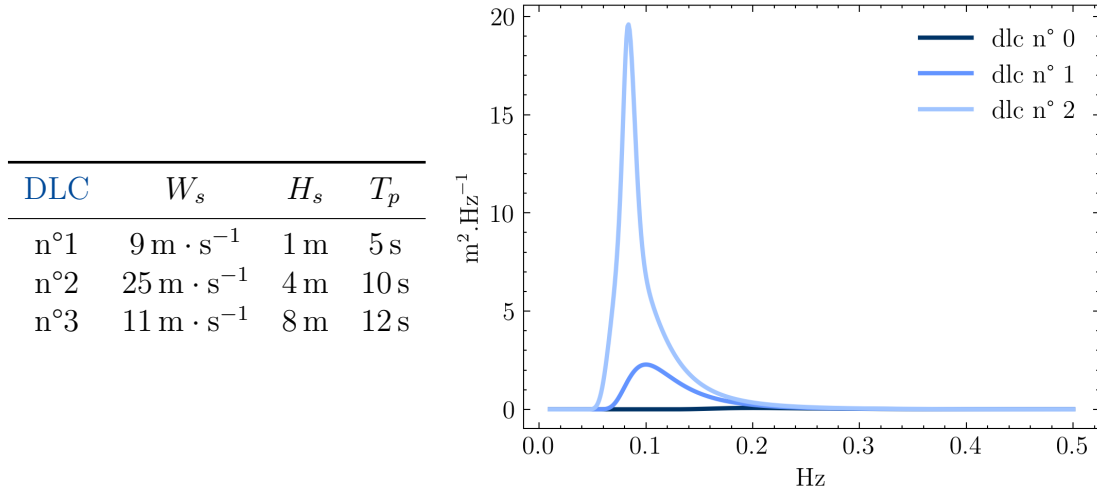


Figure 4.6. DLCs considered for analysis.

Each of these quantities is estimated using RAFT, based on the mean steady state of the FOWT system and its FD dynamic response, from which a maximum value can be determined. These values are computed for each defined DLC, and the maximum result across all cases is selected to be checked against the constraint limits of the optimization problem. Defining these constraint limits to accurately represent real-world conditions can be challenging, so they are often set to general values based on experience. This approach is also applied here, supported by insights from previous optimization and simulation studies, such as those in [110], and other publicly available RAFT models. To evaluate different platform designs capable of supporting large OWTs, a broad range of 20 m to 60 m is considered for the width of the GICON[®]-TLP. The steel pipes used in the UBB construction are adapted from wind turbine tower and monopile designs, with typical diameters between 5 m and 15 m. For additional geometric flexibility, a slightly broader range of 5 m to 20 m is considered for both the length and diameter of the UBB. The vertical position of the UBB is constrained by the platform's draft and the MSL, within a fixed range of 5 m to 20 m.

The constrained single-objective design optimization problem for the GICON®-TLP is defined as follows:

$$\begin{aligned}
&\text{minimize:} && m_{tlp}, \\
&\text{subject to:} && D \in [20 ; 60] \text{ m}, \\
& && l_{ubb} \in [5 ; 30] \text{ m}, \\
& && d_{ubb} \in [5 ; 30] \text{ m}, \\
& && z_{ubb} \in [10 ; 40] \text{ m}, \\
& && X_o \leq 8 \text{ m}, \\
& && \theta_p \leq 3^\circ, \\
& && a_{rna} \leq 0.5 \text{ m} \cdot \text{s}^{-2}, \\
& && M_{base} \leq 2 \times 10^{10} \text{ N}.
\end{aligned} \tag{4.4}$$

4.3.3. Results

The GICON®-TLP design optimization problem considered is ran 10 times to yield more robust optimization results for the final set of optimized design variables. The optimization parameters used here are similar to those applied in the validation process, with minor adjustments to compensate the computational cost associated with the RAFT simulations required at each evaluation (approximately 10 seconds) whenever the values of the objective function and constraints are calculated and verified. The optimization process begins with an initial population of 50 individuals, generated using Sobol sequences to gain a broad understanding of the extensive design space early in the process. For each generation, 20 new individuals are produced via crossover and 10 via mutation, with fixed distribution indices set at $\eta_c = 50$ and $\eta_m = 100$. The threshold distances are set to $d_0 = 0.1$ and $d_1 = 1e - 4$, and the minimum distance d_{min} for identifying local optima is set at 0.25. The statistical results from the optimization runs on this design optimization problem are presented in Table 4.5.

Table 4.5. Optimization results for the GICON®-TLP design optimization problem.

	min	max	mean	std
D	57.50	59.00	58.27	0.40
l_{ubb}	19.00	20.20	19.58	0.30
d_{ubb}	15.80	16.80	16.33	0.30
z_{ubb}	23.00	24.50	23.84	0.50
m_{tlp}	6148.136	6200.0	6148.1	25.0
X_o	7.8	8.2	8.0	0.1
θ_p	2.3	2.7	2.49	0.1
Ax_{RNA}	0.20	0.24	0.217	0.01
M_{base}	1.90e10	1.98e10	1.942e10	0.02e10

The different optimization runs generally produced similar results for the objective to minimize, with an average minimum objective value of around 6150 t. Figure 4.7 shows the evolution of the GICON[®]-TLP's mass, its corresponding dynamic response, and the tower base fore-aft bending moment across the generations of the optimization process for the global optima identified. This plot is displayed for the best of the 10 runs, showing the fittest individual in each generation as the population size increases. These results demonstrate the successful implementation of the optimization framework, resulting in an optimized design of the GICON[®]-TLP that satisfies the dynamic constraints while minimizing mass.

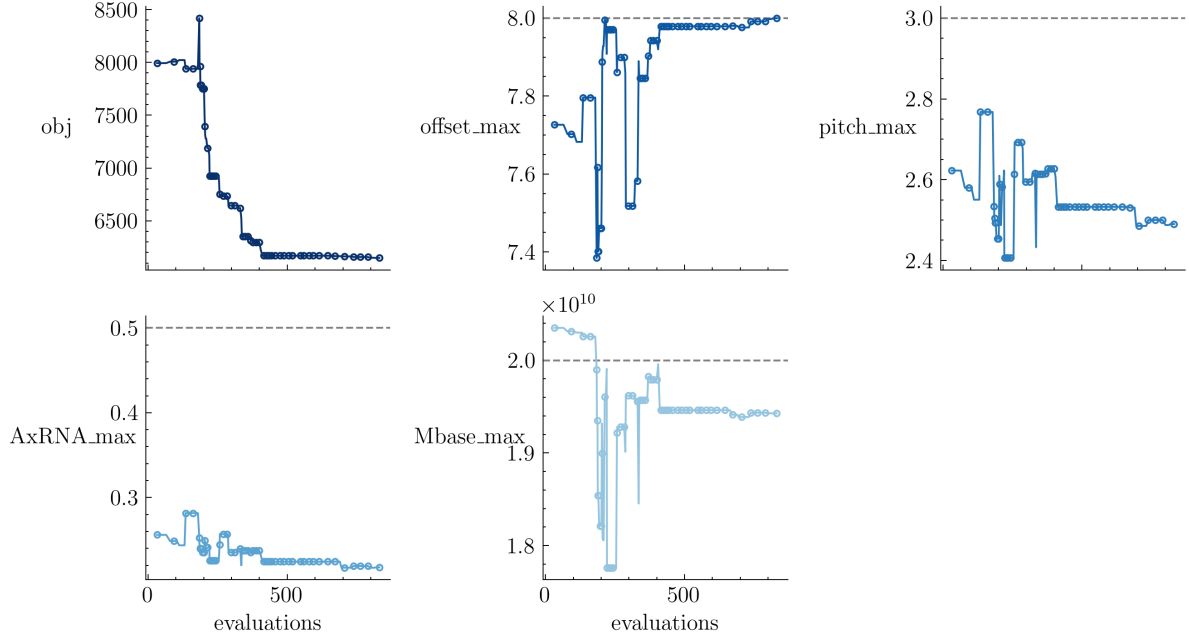


Figure 4.7. Objective and constraints evolution for the GICON[®]-TLP design optimization problem.

Table 4.6 presents the optimized design variables for the GICON[®]-TLP, including the corresponding mass and constraint values, for the design with the minimum mass achieved. The optimal substructure design features a relatively wide UBBs configuration, with a diameter larger than its length and a low center of gravity. This design minimizes substructure mass due to its compact geometry, while also providing sufficient buoyancy to positively impact system dynamics. The low center of gravity helps maintain platform stability, resulting in minimal pitch and reduced nacelle acceleration—both of which are constrained in this design. Figure 4.8 displays the RAFT model of the optimized GICON[®]-TLP in both unloaded conditions (no wind and calm water) and displaced positions across all defined DLC, with the final graph on the right showing the response under the most demanding environmental conditions. It is interesting to observe that the most demanding environmental conditions occur when the mean wind speed is close to the turbine's rated wind speed, where maximum power is generated, and is the last of the DLCs defined.

In our case, these conditions also coincide with the highest wave considered. This trend holds true for nearly every design, which is logical given that the system is modeled in the [FD](#), where loads and responses are linearly correlated. While this optimization study could potentially be simplified, it remains valuable as it assesses multiple environmental conditions using [RAFT](#) and visualizes results under varying conditions. In addition [4.9](#) illustrates the pairwise distribution of the design variables in the final population at the end of the optimization process. As expected, the final population density is concentrated in the fittest regions of the design space, where the objective is minimized, and constraints are satisfied. In addition it seems like the global optima of the problem is clearly identified with no local optima that the algorithm found worth studying.

Table 4.6. Optimized design of the [GICON[®]-TLP](#).

D	l_{ubb}	d_{ubb}	z_{ubb}	
58.27 m	19.58 m	16.33 m	23.84 m	
m_{tlp}	X_o	θ_p	a_{rna}	M_{base}
6148.136 t	7.999 mm	2.49°	0.217 m · s ⁻²	1.942 × 10 ¹⁰ N

4.4. Discussions

Overall, the optimization framework effectively identified designs that minimized the objective function while satisfying the constraints for both optimization studies conducted. This was accomplished with a relatively low number of evaluations, allowing for multiple optimization runs despite the considerable analysis time required per design. The use of a multiprocessing approach further reduced runtime by enabling evaluations to run in parallel, showcasing an additional efficiency advantage of the current design optimization framework. The first optimization study, focused on the [UBB](#) design, presented unique challenges due to the broad design space and the multiple variables and constraints involved. The results suggest that different local optima were identified within the design space, with the global solution identifiable to a certain extent. This initial optimization study, along with the numerical model, was the first to be implemented within the framework, utilizing a relatively simple analysis. A more complex and detailed analysis could potentially yield alternative results.

The global system design optimization shows promising preliminary outcomes. While it would benefit from incorporating structural analysis for a more comprehensive assessment, this framework still allows for the generation of an initial design for the substructure. This provides a valuable foundation for the preliminary design of the [UBB](#) and the [GICON[®]-TLP](#), offering a baseline geometry for future [FOWT](#) developments. Looking ahead, integrating new turbine models, such as the [IEA 22 MW model \[139\]](#), into the framework could yield even more precise design insights by incorporating the latest industry standards and performance metrics.

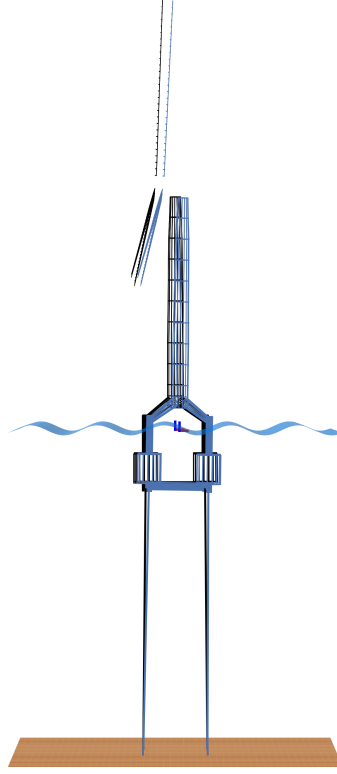


Figure 4.8. Dynamic performance of the optimized **GICON[®]-TLP** design for the worst conditions in the **DLCs** considered.

For both problems the objective was to minimize the mass and so therefore the cost. IT is now possible to asses to cost saving that can be obtained with this optimized design found. Typical costs for ship-structure floating platforms can reach $4.5 \text{ k€} \cdot \text{t}^{-1}$, while series manufacturing costs for monopiles are around $2 \text{ k€} \cdot \text{t}^{-1}$ [66]. This study assumes a unit cost of $3 \text{ k€} \cdot \text{t}^{-1}$ for steel, reflecting processes similar to those used in the **GICON[®]-TLP** and **UBB**. Concrete costs are estimated at $0.3 \text{ k€} \cdot \text{t}^{-1}$. The total cost of one **UBB** is then computed using the mass of the structure and the cost factors specified. To assess potential cost savings, the optimized **UBB** is compared with a traditional ship-structure buoyancy body and the design presented in [66]. The original **GICON[®]-TLP** buoyancy body has an estimated mass of 150 t. According to [66], the total mass of the **UBB** is around 2.6 times higher than the earlier design but approximately 0.8 times cheaper. Table 4.7 summarizes the expected cost reduction using the optimized **UBB** design for the **GICON-TLP**, suggesting a potential 25% or greater reduction in costs. It is important to notice that for both studies the results are quite sensitive to the choice of design space, constraint limits, and loading conditions. Variations in these inputs can significantly affect the optimized design, emphasizing the importance of careful control and validation of the parameters. Therefore, these results should be interpreted within the context of the specific conditions applied in this study, with further refinement

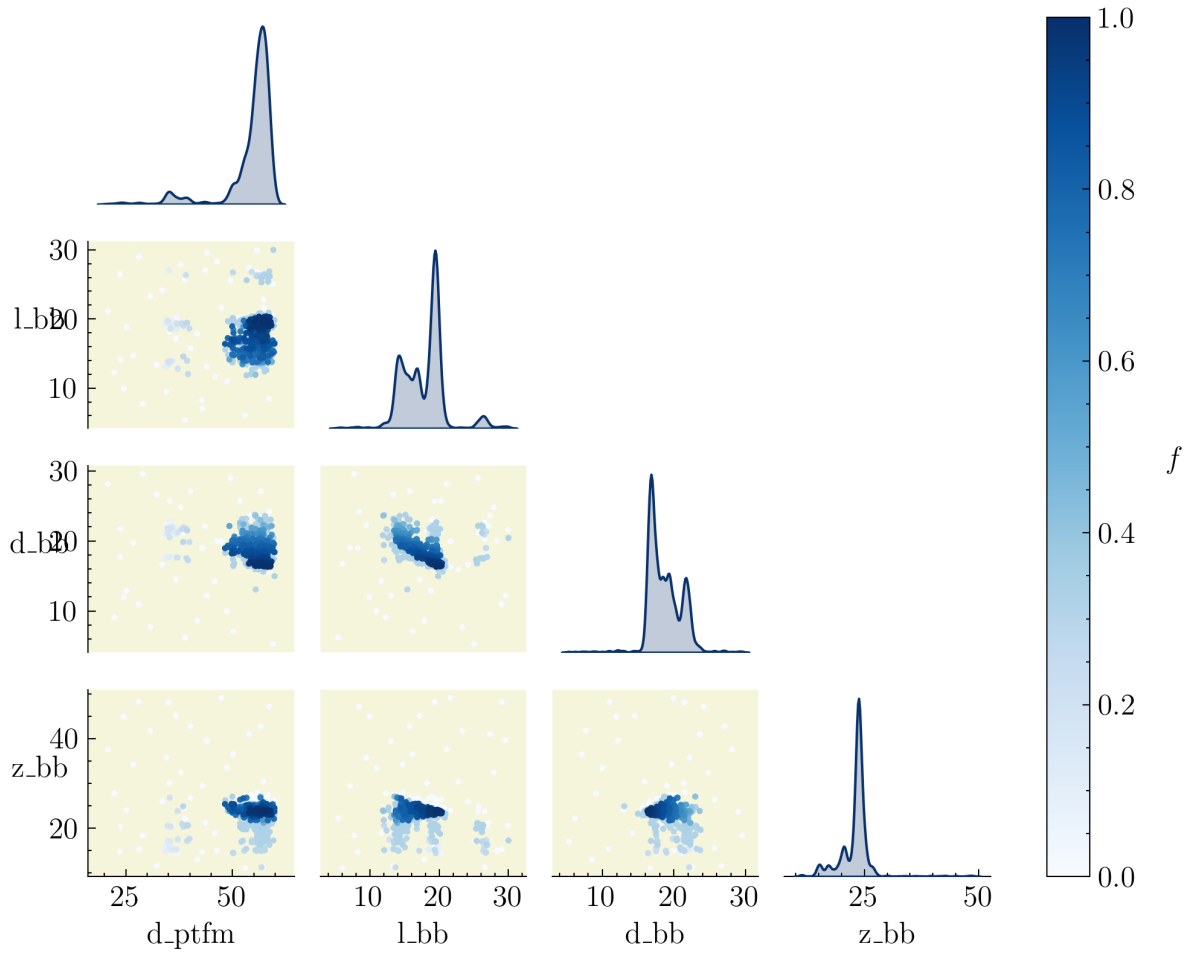


Figure 4.9. Pairwise distribution of the final population's design variables for the **GICON[®]-TLP** design optimization problem.

recommended for other scenarios.

Table 4.7. Potential for cost reduction using the optimized design of the **UBB**.

	Old BB	UBB	UBB optimized
Weight (t)	150	390	330
Cost (k€)	675	540	500
Cost reduction (%)	-	20%	25%

Conclusion

In order to limit global warming, it is crucial that conventional fossil energies are gradually replaced by renewable energies. OW energy is undeniably a key component in the transition to renewable energy. Many countries appear interested in it but remain hesitant to fully develop it. FOW is gaining momentum, and achieving cost efficiency is essential to develop future projects and harness offshore wind resources in deep waters, where fixed OWT are not economically or technically feasible. The LCoE for OW energy, particularly for FOW, must decrease significantly to remain competitive. Despite recent advancements, significant challenges remain, especially in optimizing cost efficiency and refining design processes to meet industrial demands.

Recently, various floater concepts and modular components have been developed to reduce production costs by serializing the fabrication of floating foundations. As FOWT technologies continue to develop, innovative solutions like the GICON®-TLP offer promising steps toward efficient offshore wind systems. Many academic and industrial research efforts have focused on design optimization for FOWT, particularly their floating foundations. This thesis contributes to these efforts by presenting a comprehensive framework for optimizing FOWT substructure designs. It focuses on the innovative GICON®-TLP platform and the UBB, a component designed for multi-use across different substructure types. In addition this thesis extends research on the GICON®-TLP design concept, offering a first optimization study including a large future offshore turbine to demonstrate the efficiency of such platform and integration of multi-use components that streamline manufacturing and reduce costs.

In the introduction, a detailed overview of FOW is presented, covering various aspects such as its early development, potential zones for deployment, technical requirements, and cost reduction potential. Open-source data are used to derive metocean data, allowing an assessment of FOW potential in Europe and leading to the identification of areas with high potential for floating wind farms. Notably, regions within the UK, Norway, Iceland, and Ireland emerged with substantial coverage and promising potential. Other countries with significant potential include Sweden, Finland, France, Spain, and Greece, with large areas of the Baltic Sea also suitable for FOW installations. In contrast, Mediterranean countries show lower potential due to weaker wind speeds, though the milder wave conditions may allow for smaller floaters than those required in the harsher environments of northern Europe and the Atlantic. Additionally, more than 40 % of the total EEZ of the considered countries is located in waters deeper than 1000 m, which currently poses technical challenges for floating turbine deployment. This situation, however, may change with the development of new, cost-effective installation techniques and materials.

The state-of-the-art review on FOWT substructure modeling and design optimization is presented as a baseline for developing an optimization tool, which is in the core objective of this thesis. The review covers topics related to the design of FOWT substructures, summarizing design processes and associated practices from the literature to identify key design parameters and outline potential cost reductions. One major consideration is the early integration of industrial issues in the design of offshore wind turbines. Since accurate modeling of floating systems is essential for more effective design, state-of-the-art numerical models for platform dynamics and mooring line analysis are also reviewed in this work. The review covers different modeling approaches for aerodynamic and hydrodynamic loads as well as mooring line models, with practical examples from the literature. Lastly, work on FOWT optimization, alongside related numerical models and design practices, is summarized. Several existing academic and industrial studies on the design optimization of floating substructures are reviewed and are summarized here.

A key outcome of this thesis is the presented optimization framework specifically implemented for the design optimization of the GICON®-TLP and its multi-use component the UBB. This component allows for a relatively fast manufacturing process and can adapt to different floater structural designs. The framework combines an efficient GA process with validated numerical tools. Preliminary results for a specific case study led to a cost-optimized UBB design with conical covers that meet buoyancy and structural strength requirements. The results highlight the optimization process's efficiency in terms of fitness function evaluations, emphasizing the potential of this approach to reduce costs and manufacturing time for FOWT foundations. A second study applied the framework with a validated FD dynamic model, leading to a cost-optimized GICON®-TLP design that met the required dynamic constraints under various environmental conditions. The framework offers several advantages, including speed, due to the frequency-based approach, and a low number of fitness function evaluations that help avoid unnecessary design assessments. The case studies demonstrate the framework's capability, showcasing potential cost reductions through optimized design and the integration of adaptable multi-use components.

The thesis has made several contributions, including coupled analysis of FOWT, considerations of manufacturing, transportation, and installation concerns and design optimization. Additionally, the application of standardized components for FOWT, which have been limited until now, can address extended fabrication and assembly times that increase costs. For instance, the cylindrical UBB design is proposed as a standardized buoyancy body adaptable for semi-submersible or TLP. Ultimately, the three main objectives and tasks outlined in the introduction can be considered achieved, as this thesis has provided a state-of-the-art review relevant to FOWT substructure design optimization, developed a design optimization tool using open-source resources, and contributed to LCoE reduction for FOW energy by applying this framework to a specific design that integrates multi-use components.

5.1. Outlooks

Further improvements are planned for the work presented in this study. The floating offshore wind energy potential review provides a high-level overview based on selected criteria, but it currently omits critical aspects of maritime spatial planning, such as existing infrastructure like ports and electrical networks, soil type, and various restrictions that may hinder development. These factors are essential in determining practical deployment zones and will be critical in refining potential analyses. For instance, areas initially identified as suitable for floating wind may, upon closer analysis, be constrained by factors such as existing maritime use, protected zones, or prohibitive deployment costs. Thus, a more detailed future analysis incorporating these constraints and integrating data from maritime spatial plans will help identify realistic opportunities for FOW deployment. Including stakeholder perspectives, such as local regulations and environmental considerations, could further refine the feasibility of these areas and increase alignment with national energy strategies.

The optimization framework presented in this thesis also shows room for significant future enhancements. First, alternative genetic operators and constraint-handling techniques could be explored to enhance optimization robustness. The inclusion of other evolutionary algorithms, such as differential evolution or particle swarm optimization, could potentially improve computational performance, depending on the complexity of the design problem. Implementing a batch analysis approach to evaluate multiple designs in parallel could address one of the main computational challenges, significantly reducing overall computation time. Additionally, developing a user interface for the optimization tool would increase accessibility, allowing researchers and industry practitioners to apply the tool with ease.

The next step in advancing the UBB design is to transition to a more detailed structural model. The current model of the UBB is relatively simplified, covering essential strength requirements. Future enhancements will introduce additional structural loads, especially hydrodynamic loads, which are critical for certain floating substructures. By refining the model to encompass the full FOWT system, including the platform, turbine, and mooring lines, future studies could conduct integrated design optimization that considers various limit states specified in offshore standards. This more holistic approach would provide a more comprehensive and resilient design capable of withstanding complex environmental loads. From a design evolution perspective, the UBB concept is relatively new and continues to be refined. For instance, the possibility of casting parts of the inner pipe is being investigated to reduce the number of welds in high-stress zones, thus improving structural reliability and simplifying manufacturing. Such a modification would require adjustments in both the structural model and analysis methods. Additionally, the potential integration of the UBB into other floating foundation types, such as semi-submersibles or spar platforms, could further expand its application. By adapting and optimizing the UBB for different substructure designs, future work could unlock a modular approach that supports various floating wind technologies, making it more versatile and attractive to the industry.

Regarding dynamic response, the current framework employs **RAFT** with strip-theory hydrodynamics and linearized quasi-static mooring dynamics. Future work could benefit from more advanced hydrodynamic models, such as those using potential flow theory, to enhance accuracy in capturing complex interactions between the floater and the marine environment. Fatigue analysis is another key area for improvement; time-domain simulations, essential for **FOWT** design, will be integrated using tools like OpenFAST, with **RAFT** functioning as a pre-processor. These time-domain models can simulate transient conditions and provide a detailed understanding of fatigue loads, enhancing the life time and reliability of **FOWT** substructures. Expanding the design space to include variables such as pipe thickness and other geometric properties of structural components would allow for a more exhaustive exploration of the optimization possibilities, ensuring that the most cost-effective and structurally sound designs are achieved.

The cost model employed in this study is also relatively simple, relying on experience-based values for material and manufacturing costs. Future enhancements could improve accuracy by incorporating additional cost factors related to installation, transportation, and production processes. A more comprehensive cost model that accounts for these factors would provide a more realistic assessment of the total project cost. However, a robust cost model presents challenges due to limited data availability. Collaboration with industry partners may also help obtain more accurate cost data, further refining the model's reliability.

Looking forward, integrating new turbine models into the framework could yield even more precise design insights by incorporating the latest industry standards and performance metrics. This would allow the framework to stay current with the industry's rapid advancements and produce optimized designs that are both cost-effective and performance-driven. Additionally, as turbine sizes increase, examining their interactions with substructure designs will be vital in addressing scaling challenges and maintaining stability and efficiency. These proposed advancements underscore the flexibility and adaptability of the current framework, making it a valuable tool for future developments in **FOWT** substructure design optimization.

Appendix

A. Additional Metocean Data in Europe

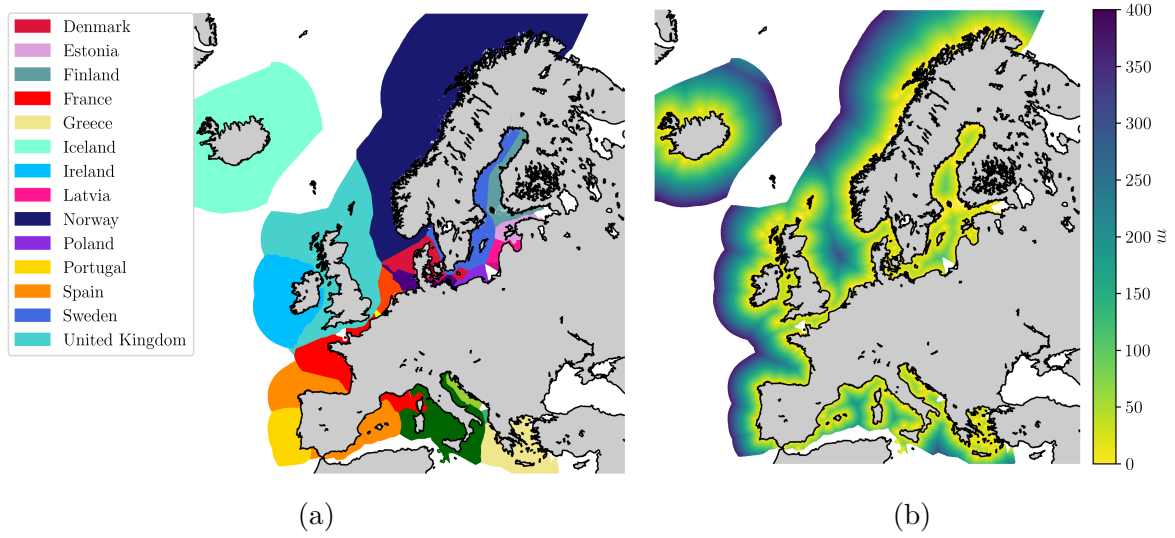


Figure A.1. EEZs and distance to the shore in Europe.

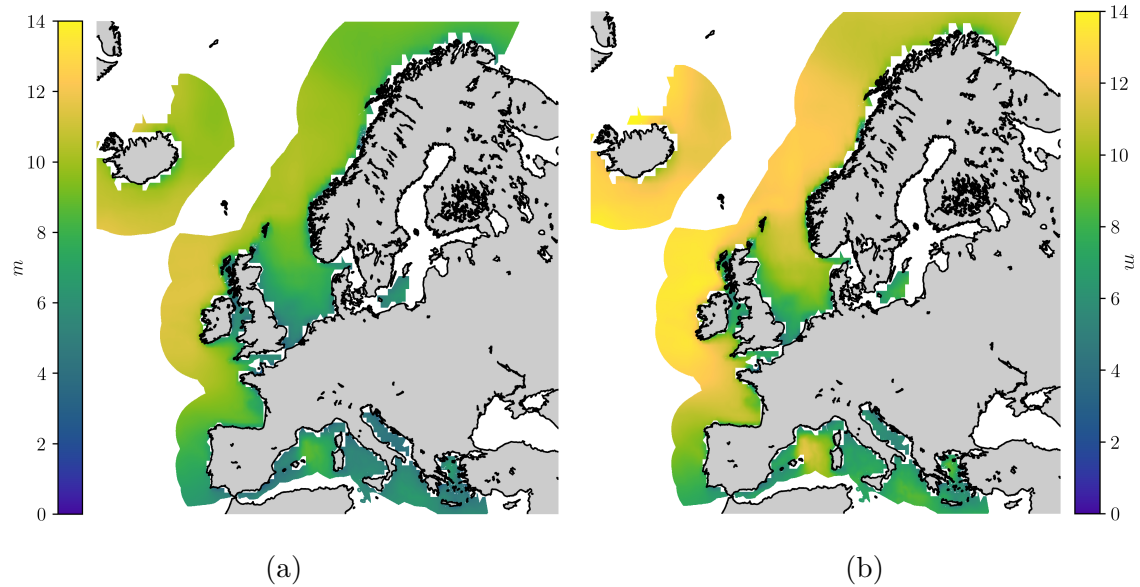


Figure A.2. Extreme significant wave heights with return period of 1 (a) and 20 (b) years in Europe.

***All areas provided in the following tables are accurate to about $\pm 5\%$, which is due to the grid resolution of the bathymetry, EEZ and metocean data.*

Table A.1. Area covered by OW farm types.

Country	Fixed OW	Hybrid OW	1 st gen. FOW	2 nd gen. FOW	Future gen. FOW	Area (in 10 ³ km ²)
Albania	2	2	3	4	-	11
Belgium	3	-	-	-	-	3
Croatia	15	12	20	3	5	55
Denmark	89	13	3	-	-	105
Estonia	22	10	4	-	-	36
Finland	52	18	10	-	-	80
France	55	34	83	16	155	343
Germany	54	-	-	-	-	54
Greece	22	19	60	85	261	447
Iceland	20	20	106	104	353	603
Ireland	19	39	120	53	194	425
Italy	42	29	61	86	318	536
Latvia	17	4	7	-	-	28
Lithuania	5	2	-	-	-	7
Netherlands	63	-	-	-	-	63
Norway	37	58	277	112	267	751
Poland	17	11	1	-	-	29
Portugal	7	6	14	14	273	314
Spain	20	21	41	59	420	561
Sweden	78	41	35	1	-	155
UK	161	176	208	46	138	729
Total	801	516	1053	584	2384	5338

Table A.2. Area covered by wind speed classes.

Country	Class IV	Class III	Class II	Class I	Class I+	Area (in 10^3 km^2)
Albania	8	4	-	-	-	12
Belgium	-	-	1	2	-	3
Croatia	33	22	-	-	-	55
Denmark	-	1	10	54	40	105
Estonia	-	3	12	21	-	36
Finland	-	10	25	46	-	81
France	19	50	85	191	-	345
Germany	-	2	9	37	9	57
Greece	67	218	122	41	-	448
Iceland	1	10	15	44	535	605
Ireland	-	1	7	36	384	428
Italy	212	305	19	-	-	536
Latvia	-	1	7	20	-	28
Lithuania	-	-	2	5	-	7
Netherlands	-	1	3	56	3	63
Norway	21	24	40	476	191	752
Poland	-	2	8	21	-	31
Portugal	1	21	200	93	-	315
Spain	87	165	78	232	-	562
Sweden	-	16	43	96	-	155
UK	-	5	27	272	427	731
Total	450	863	713	1744	1589	5359

Table A.3. Area of potential FOW deployment sites.

Country	Area (in 10^3 km^2)
Denmark	12
Estonia	12
Finland	27
France	83
Greece	43
Iceland	178
Ireland	126
Latvia	11
Norway	300
Poland	11
Portugal	9
Spain	22
Sweden	68
UK	314
Total	532

B. Optimization Test Problems

B.1. Problem Definitions

The Three-Hump-Camel function is defined as in [136]:

$$\begin{aligned} \text{minimize:} \quad & f = 2x^2 - 1.05x^4 + \frac{x^6}{6} + xy + y^2, \\ \text{subject to:} \quad & x, y \in [-5 ; 5]. \end{aligned} \quad (.1)$$

The Schwefel function is defined as in [136]:

$$\begin{aligned} \text{minimize:} \quad & f = 2 \times 418.9829 - \left(x \sin(\sqrt{|x|}) + y \sin(\sqrt{|y|}) \right), \\ \text{subject to:} \quad & x, y \in [-500 ; 500]. \end{aligned} \quad (.2)$$

The Hartmann function is defined as in [136]:

$$\begin{aligned} \text{minimize:} \quad & f = - \sum_{i=1}^4 \alpha_i \exp \left(- \sum_{j=1}^6 A_{ij} (x_j - P_{ij})^2 \right), \\ \text{subject to:} \quad & x_i \in [0 ; 1]. \end{aligned} \quad (.3)$$

with:

$$\begin{aligned} \alpha &= \begin{bmatrix} 1.0 \\ 1.2 \\ 3.0 \\ 3.2 \end{bmatrix}, \\ A &= \begin{bmatrix} 10 & 3 & 17 & 3.5 & 1.7 & 8 \\ 0.05 & 10 & 17 & 0.1 & 8 & 14 \\ 3 & 3.5 & 1.7 & 10 & 17 & 8 \\ 17 & 8 & 0.05 & 10 & 0.1 & 14 \end{bmatrix}, \\ P &= 10^{-4} \times \begin{bmatrix} 1312 & 1696 & 5569 & 124 & 8283 & 5886 \\ 2329 & 4135 & 8307 & 3736 & 1004 & 9991 \\ 2348 & 1451 & 3522 & 2883 & 3047 & 6650 \\ 4047 & 8828 & 8732 & 5743 & 1091 & 381 \end{bmatrix}. \end{aligned} \quad (.4)$$

The Sphere function in n dimension is defined as in [136]:

$$\begin{aligned} \text{minimize:} \quad & f = \sum_i^n x_i^2, \\ \text{subject to:} \quad & x_i \in [-1 ; 1]. \end{aligned} \quad (.5)$$

The constrained Gomez-Levy function is defined as in [137]:

$$\begin{aligned}
 \text{minimize:} \quad & f = 4x^2 - 2.1x^4 + \frac{x^6}{3} + xy - 4y^2 + 4y^4 \\
 \text{subject to:} \quad & x, y \in [-1 ; 1], \\
 & g = 2 \sin^2(2\pi y) - \sin(4\pi x) \leq 1.5,
 \end{aligned} \tag{.6}$$

The welded beam design optimization problem is defined as in [129]:

$$\begin{aligned}
 \text{minimize:} \quad & f = 1.10471h^2l + 0.04811tb(14 + l), \\
 \text{subject to:} \quad & h \in [0 ; 1], \\
 & l \in [0 ; 1], \\
 & t \in [0 ; 1], \\
 & b \in [0 ; 1], \\
 & T \leq 13600, \\
 & \sigma \leq 30000, \\
 & h \leq b, \\
 & 6000 \leq P_c, \\
 & \delta \leq 0.25
 \end{aligned} \tag{.7}$$

with:

$$\begin{aligned}
 T &= \sqrt{\tau_1^2 + \tau_2^2 + \frac{l\tau_1\tau_2}{\sqrt{0.25(l^2 + (h+t)^2)}}}, \\
 \tau_1 &= \frac{6000}{\sqrt{2}hl}, \\
 \tau_2 &= \frac{6000(14 + 0.5l)\sqrt{0.25(l^2 + (h+t)^2)}}{20.707hl\left(\frac{l^2}{12} + 0.25(h+t)^2\right)}, \\
 \sigma &= \frac{504000}{t^2b}, \\
 P_c &= 64746.022(1 - 0.0282346t)tb^3, \\
 \delta &= \frac{2.1952}{t^3b}.
 \end{aligned} \tag{.8}$$

B.2. Optimization results

***All results provided in the following tables are the statistical results for 10 optimization runs. The initial population is generated using Sobol sequences (using the same seed for consistency), with sizes ranging from 50 to 100 individuals, 20 individuals are generated through crossover and 10 through mutation, using fixed distribution indices of $\eta_c = 50$ and $\eta_m = 100$, respectively. The distances used in the threshold are set to $d_0 = 0.1$ and $d_1 = 1e - 4$, and the minimum distance d_{min} for local optima identification is set at 0.1, except for the Sphere function, where a value of 0.25 is applied. The maximum population size is capped at a maximum of 5000 individuals.*

Table B.4. Optimization results for the Three-Hump-Camel function.

	min	max	mean	std
x	-0.000272	0.000354	-0.000020	0.000229
y	-0.000251	0.000498	0.000106	0.000236
f	0.000000	0.000000	0.000000	0.000000

Table B.5. Optimization results for the Schwefel function.

	min	max	mean	std
x	420.907341	421.053811	420.989863	0.048171
y	420.000106	421.066889	420.953538	0.065480
f	0.000106	0.002029	0.000861	0.000698

Table B.6. Optimization results for the Hartmann function.

	min	max	mean	std
x_0	0.201454	0.201848	0.201692	0.000115
x_1	0.149669	0.150237	0.149985	0.000143
x_2	0.476851	0.477035	0.476928	0.000062
x_3	0.275220	0.275463	0.275375	0.000087
x_4	0.311376	0.311854	0.311614	0.000125
x_5	0.657127	0.657535	0.657267	0.000160
f	-3.322368	-3.322363	-3.322366	0.000002

Table B.7. Optimization results for the Sphere function in dimension 10.

	min	max	mean	std
x_0	-0.0000	0.0005	0.0001	0.0002
x_1	-0.0003	0.0008	0.0001	0.0004
x_2	-0.0004	0.0004	0.0000	0.0003
x_3	-0.0006	0.0004	0.0000	0.00050
x_4	-0.0007	0.0006	-0.0002	0.0005
x_5	-0.0005	0.0004	-0.0001	0.0004
x_6	-0.0006	0.0005	0.0001	0.0004
x_7	-0.0007	0.0005	0.0000	0.0003
x_8	-0.0008	0.0005	0.0001	0.0003
x_9	-0.0006	0.0005	0.0001	0.0004
f	0.000000	0.000001	0.0000	0.0000

Table B.8. Optimization results for the Gomez-Levy function.

	min	max	mean	std
x	0.089627	0.089929	0.089792	0.000096
y	-0.712776	-0.712554	-0.712650	0.000069
f	-1.031628	-1.031628	-1.031628	0.000000
g	0.987070	0.989055	0.988148	0.000586

Table B.9. Optimization results for the welded beam design optimization problem.

	min	max	mean	std
h	0.238	0.373	0.305	0.048
l	4.853	8.116	5.763	1.036
t	6.126	8.170	7.286	0.664
b	0.256	0.452	0.333	0.062
f	2.481	3.364	2.855	0.322
$T(x)$	12433	13599	13245	367
$\sigma(x)$	26883	29995	29160	1065
$P_c(x)$	30236	6795	14650	7199
$\delta(x)$	0.015	0.021	0.018	0.002

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