

The authors would like to thank the reviewers for the constructive recommendations and comments which will help improve the current and future work. In the following, the authors would like to respond to the reviewers' comments. The addressed comments are included in italic font.

### **Answers to RC1:**

1. *page 1, line 45. The author does not provide an adequate literature review of the current state of the art in optimization of floating wind turbine support structures, except listing eight papers. The authors should, the studies related to single objective optimization, gradient-free optimization, and spar-buoy floater, which are most relevant to the study in this paper. Besides, there are also studies of multi-objective GA optimization of floating wind turbine support structures, which are also relevant to this study. Additionally, how the mooring system is treated in the relevant studies? After an adequate literature review, the authors need to justify the value and contribution of this work.*

The authors extend this paragraph and add a more detailed literature review on optimization applications of spar-type floating wind turbine support structures. The separate aspect of optimizing the mooring system is now included and addressed in more detail in Section 2.3 (paragraph in lines 188-195 on page 7).

2. *page 7, line 190. A general comment is related to the assumption that the mooring system is kept constant in this study. the mooring system is composed of a few mooring lines. Did the authors use constant values for the horizontal and vertical stiffness of each mooring line? Or, did the authors use a constant mooring stiffness matrix for the entire mooring system? The former approach is more reasonable, because the floater pitch stiffness depends on the product of the horizontal stiffness of mooring line and the radius of the fairlead. Can the authors predict what is the impact of their assumption on the optimized designs? The optimizer may take advantage of the assumption. Can the authors improve the way to treat the mooring system? This minor improvement can provide a more realistic way to include the mooring system. Alternatively, the authors may consider provide a representative design of the mooring system that satisfies the mooring stiffness for the chosen optimized design. Such practice and guide would make the methodology in the study more convincing.*

The realization of the mooring system and the use of the resulting mooring system properties follows the first approach mentioned by the reviewer. Each mooring line is specified through its length, diameter, mass in water, extensional stiffness, added mass coefficient, drag coefficient, damping coefficient for inner damping, fixation point at anchor, as well as fixation point at fairlead. As mentioned (line 189 on page 7) the mooring system itself can cover a separate optimization. This is now underlined in more detail by added literature (as indicated in 1. as well). These literatures also confirm that, following the applied approach, a corresponding mooring system design, which represents the same resulting mooring system properties but matches possible attachment points on the optimized floater geometry, can be obtained through a separate subsequent optimization. The literature as well emphasizes the mentioned aspect (lines 192-195) that the system performance can further be improved through a subsequent optimization of the mooring system.

3. *page 17, section 4.3.2. The authors classify the optimizers into single-objective optimizers and multi-objective optimizers. It is a little confusing. While single-objective and multi-objective optimization are widely used, this often points to the formulation of the optimization problem, rather than the optimizer. The performance of the optimizer highly depends on the algorithm itself. On the other hand, for example, GA can be used to solve both single-objective and multi-objective optimization problem as stated by the authors. In a strict way, GA can be called single-objective and multi-objective optimizer. The authors may re-write this paragraph to avoid the confusion and directly highlight that they are using GA algorithm.*

The paragraph is reformulated, to ensure that the currently termed single-objective and multi-objective optimizers mean optimizers that can deal with single-objective and multi-objective formulated optimization problems.

4. *page 30, line 658. This study lacks a verification of the optimized design. Can the authors verify the hydrodynamic properties of the floater by using high-fidelity tools such as WAMIT?*

Unfortunately, the authors do not have a license to other high-fidelity tools, such as WAMIT, for performing a verification of the specific optimized design. The hydrodynamic properties and calculations performed within MoWiT are verified for other geometries (OC3 spar-buoy, OC6 semi-submersible, but also a large diameter bottom-fixed monopile or the OC5 jacket), where data from other tools for comparison was available. As pointed out on page 30, the proposed realization of the optimized spar-buoy floater design without having that strongly constricted shape or instead of this using a tapered connection between the upper column and the bottom part of the base column, but with utilizing tendons for connecting the bottom part of the base column to the upper column, will not experience the shortcomings of the hydrodynamic calculation approaches.

5. *page 32, line 725. This study assumes a rigid floater with a constant thickness. However, the chosen final design has a neck-like weak feature. The authors noted in the conclusion that this can be manufactured by using truss structures. Can the authors further illustrate this? Further, how would this bias the cost and performance of the chosen design?*

The innovative structural realization opportunities are explained in lines 513-520 on pages 22/23, lines 571-579 on page 27, and lines 679-683 on page 31. Here it is meant that the bottom part of the base column can be connected to the upper column by means of tendons or truss elements. Thus, it is not meant that the optimized spar-buoy geometry is fully replaced by a truss structure, but instead of having tendons between upper column and bottom part of base column, also rigid braces/truss elements might be used. As mentioned in lines 575-577 on page 27, it is expected that such an alternative structural realization – if it represents a rigid connection – will represent similar system performance. With respect to the costs, it might be more comparative to use tendons instead of truss elements, however, this would imply a more detailed analysis including manufacturing costs in addition to material costs.

6. *A general comment is related to the computation time for the optimization problem. How long does it takes? Can the authors provide such information?*

The information on the computation time has already been provided in line 463 on page 19.

7. *Another general comment is related to the interpretation of the optimized design. The authors have noted its similarity with TetraSpar. Can the authors compare the system properties of the baseline design and the optimized design? For example, the buoyancy and mass centers of the entire wind turbine, the eigen-frequencies of the coupled floater-tower vibration mode?*

The authors reformulate the statement to ensure that the similarity of the optimized spar-buoy floater with TetraSpar is purely meant with respect to the innovative structural realization approach and not referring to the specific system properties.

Thanks as well for the minor comments added. Even if the reviewer leaves for some points the final decision on the implementation to the authors, the authors also would like to respond to these comments.

1. *page 10, section 3. It is better to modify the formulation of the optimization problem into a single-objective optimization, which is the case in this study.*

By setting  $l = 1$ , as done in Section 3.2 on page 11, the prevailing case of a single-objective optimization problem is defined.

2. *page 10, section 3.1. It may be easier to follow, if the design variables are replaced with  $d_i$  and  $h_i$ . Alternatively, one can also use  $du, dm, dl, hu, hm, hl, hb$ . But it does not affect the results. It is up to the authors.*

The authors prefer to follow the general formulation of an optimization problem with design variables  $x_i$ , objective functions  $f_i$ , equality constraints  $h_i$ , and inequality constraints  $g_i$ . Thus, and as the definition of the design variables  $x_i$  is clearly given in Section 3.1, the authors stay with the used terms  $x_i$ .

3. *page 11, line 305. "It is not practical to simulate ... the full set of DLCs". It is better to put "the full set of DLCs" right after "simulate".*

The sentence is reordered accordingly.

4. *page 11, line 307. "... might be relevant and driving the design ...". It may be changed to "... may be relevant or design driving ..."*

The sentence is adjusted accordingly.

5. *page 17, line 407-412. The sentence is too long. It can be divided into three sentences.*

Due to the adjustments made based on the reviewer's main comment number 3, the long sentence referred to in this comment is no longer existing.

6. *page 23, Fig. 5. It is better to remove the baseline design. The text in the legend "original desing" may be "original design". The text "optimum individual" means the final chosen optimized design, which may not be the global optimum. "optimum individual" may be replaced with "optimized design".*

The authors intend by plotting the baseline design to allow an easier and faster (visual) comparison of the presented example designs, as this way it is shown that always a similar scale is presented and the example geometries can always be put in relation to the one and the same baseline design. The text in the legend is adjusted according to the comments.

7. *page 26, Fig. 7. It is better to put the baseline design and the optimized design side by side. Then it is clearer to see the difference between the two designs.*

For the authors it is rather easier to compare the designs and clearer to see the differences in both heights and diameters, when having both geometries plotted in one picture and having the geometries distinguished through using different colors.

8. *page 31, line 673, "where trusses or tendons prevent any utilization of strongly tapered sections". Do the authors want to mean that the trusses or tendons support the use of strongly tapered sections?*

By means of this sentence it is meant that by allowing for alternative and innovative structural realization approaches, such as the use of tendons or truss elements, a strongly tapered section, which would be required when just following the common structural realization approach, would no longer be required.

9. *page 32, line 725. The sentence is too long.*

This is the automatically generated author contributions statement, as required by the format of the journal.

## Answers to RC2:

1. *There are some weaknesses in the methods and results that could be improved to make a stronger paper. For instance, due to these simplifying assumptions, the optimized design geometries are quite surprising and raise as many questions as answers. The authors acknowledge that these are more qualitative and instructive design geometries than immediately applicable, but in that case more sensitivity studies and trade-off studies should be executed. Also, the presentation of the methods and results is fairly long winded and somewhat repetitive. Efforts could be made to tighten up the language and organization. However, instead of discussing these weaknesses in more detail, I am more concerned with the uniqueness and level of contribution of this paper.*

On the first view, the presented approach might seem to follow more simplifying assumption than other studies on optimizing spar-buoy floating wind turbine support structures. However, as outlined in the introduction (lines 49-51 and 56-59 on page 3) and discussed in more detail throughout the paper (lines 199-203 on page 7, 513-520 on pages 22/23, lines 571-579 on page 27, and lines 679-683 on page 31, lines 695-698 on page 31) the less restricted optimization problem is chosen well-considered and deliberately, to allow the consideration of novel design solutions, including alternative manufacturing approaches and structural realization methods. The common optimization approaches and defined optimization problems consider spar-type structures, which are manufactured by welding cylindrical or tapered elements together. Due to the critical aspect of having large taper angles (as addressed in lines 658-673 on pages 30/31), as well as based on the structural aspects for the commonly manufactured floater designs, the range of potential optimized floater designs and shapes is limited. However, the manufacturing solution, such as choosing between welded conical sections and tendons or truss elements for connections, cannot directly be implemented in an optimization approach. Thus, the final solution has to be selected subsequent to the optimization. But in order to not prevent innovations, thus, this paper addresses an approach to be more open-minded and allow for alternative manufacturing approaches and structural realization methods. Thus, more design variables are defined and the corresponding allowable value ranges are specified well thought out to include the aspect of innovativeness. This approach shows a novel contribution to the future design development of floating offshore wind turbine support structures. The novelty and innovativeness of the proposed approach and resulting optimized design is substantiated by the fact that the potential structural realization approaches resemble the highly innovative concepts followed in research projects (AFLOWT, TetraSpar).

2. *If I do a literature search on the keywords “floating spar optimization”, I get many hits and papers going back at least 15 years, only some of which are mentioned by the authors. Some of these papers also build on the OC3 spar that the authors have chosen for their baseline and/or use genetic algorithms to explore the design space as is done here. Furthermore, many of these papers do not make the same simplifying assumptions as this work does, leaving me to think that I should trust those other papers more. This also leads me to wonder what the novel contribution to the literature here is. I do not see that clearly stated in the paper.*

The authors add a more detailed literature review (paragraph from lines 44 to 59 on pages 2 and 3) on optimization applications of spar-type floating wind turbine support structures and point out the differences of the followed approach presented in this paper compared to other approaches found in the literature. This underlines the novel contribution of this paper, as answered also in detail in comment number 1. Thus, this freer optimization formulation of the project can allow out of the box thinking and potentially push for more disruptive designs, which can unlock the potential of floating wind.

3. *An even more significant concern for me is the similarity between this paper and a previous one already published by the authors that also does a similar optimization of the OC3 spar with a GA: <https://doi.org/10.1016/j.oceaneng.2020.107186>. Much of the material here on the methods and discretization is nearly identical to their previous paper and leaves me to wonder why these two efforts were not combined. To me, this submission has not done enough to separate itself from the authors' prior work and perhaps also not enough to separate itself from the prior work of others. What is different just doesn't meet the bar of its own journal paper, so perhaps a conference setting would be more appropriate. I am willing to hear the authors retort to my concerns, but I am inclined to decline this submission.*

This paper built on, but has a completely separate aim from the previous publication by the authors (<https://doi.org/10.1016/j.oceaneng.2020.107186>). In the previous publication, the basic three design variables (one column with a height and diameter, as well as the ballast density), common to define a standard spar-buoy floater, are selected and the considered allowable value ranges follow directly the focus of reducing costs, material, and outer dimension, while the cost itself is not specified as objective. The work presented in that previous publication deals with a very simple structure and related simple optimization approach and also mainly deals to prove the validity of the applied optimization framework and approach. This paper submitted now to WES is substantially different and significantly advances the work already completed by the authors. This paper considers a more realistic geometry, which implies as well different methods and approaches (other and more design variables, not cost-driven but broader and well thought out selected allowable value ranges, formulation of the optimization problem directly for cost reduction, open-minded approach allowing for alternative structural realization methods and innovation). Based on this paper and applied approach, the way towards more realistic analyses, with more DLCs included and coupled with structural analyses, is as well paved.

## Answers to EC1 / EC2:

1. *page 2, lines 35-37. It may be worth noting that the Fukushima Forward project in Japan tested together three different wind turbines connected to the same floating substation. It was the first floating wind farm, but with only a limited operating life as units were prototypes.*

This aspect is included in an additional note, when mentioning the Hywind Scotland pilot park.

2. *page 3, line 50. Beware: Advanced-spar may be protected by copyright by JMU (Japan-Marine-United) as it is the name of their concept.*

The authors could not find any information on the question if the term “advanced spar” is protected by copyright by JMU. However, it is ensured that the pure term “advanced spar” is only used in relation to the Fukushima Floating Offshore Wind Farm Demonstration Project FORWARD and otherwise the terms “advanced spar-type ...” or “advanced geometry spar” are used throughout the paper.

3. *page 3, lines 56-59. Does this mean that the structural arrangement is not considered in the optimization process ? Rewording may be useful.*

The original sentence “The focus of the optimization procedure lies on hydrodynamic and system-level analyses and no further limitations regarding a high detail structural design are added.” is reformulated into “The focus of the optimization procedure lies on hydrodynamic and system-level analyses and not that stringent limitations on the structure and dimensions are required.”.

4. *page 4, lines 104-107. It may be pointed that the ballasting operations of this unit proved complex: the hull accidentally listed more than 30degrees when it was brought to a deeper draught than the construction draught.*

A sentence on this issue is added.

5. *page 6, lines 170-172. The ratio of structure mass to volume on the Hywind demonstrator is in excess of 0.17.*

A note is added that the Hywind demonstrator is for safety reasons oversized and the given ratio of 0.13 is based on representative values from research designs and academic studies.

6. *page 13, lines 315-317. Load cases with transient loads (grid loss + gust) usually give rise to high accelerations and loads. It would be useful to clarify why they were not considered.*

This aspect is addressed in the discussion chapter by additional remarks added at the end of the first main paragraph in Chapter 6.

7. *page 13, Table 3. Although sufficient for the demonstration of the optimisation method, using only one wave period may not be sufficient to capture the influence of the change of natural periods in the iterative optimisation process. A discussion / warning on this point should be added in the paper.*

This aspect is addressed in the discussion chapter by additional remarks added at the end of the first main paragraph in Chapter 6.

8. *page 14, line 334. Simulation times as low as 600s do not allow to capture the low frequency dynamics of the floating wind turbines. It is understood that this is sufficient for the purpose of demonstration of the process, but this cannot be considered in the design process of a structure to be built.*

This aspect is addressed in the discussion chapter by additional remarks added at the end of the first main paragraph in Chapter 6.

9. *page 27, lines 573-577. Or using plated partial bulkheads for loads transfer.*

This aspect is included in an additional note.



# A fully integrated optimization framework for designing a complex geometry offshore wind turbine spar-type floating support structure

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**Abstract.** Spar-type platforms for floating offshore wind turbines are considered suitable for commercial wind farm deployment. To reduce the hurdles of such floating systems to become competitive, a fully integrated optimization framework is applied to design an advanced spar-type floater for a 5 MW wind turbine. Three cylindrical sections with individual diameters and heights, as well as the ballast filling height are the modifiable design variables of the optimization problem. Constraints regarding the geometry, ballast, draft, and system performance are specified. The optimization objective to minimize the floater structural material shall represent the overall goal of cost reduction. Preprocessing system simulations are performed to select a critical design load case, which is used within the iterative optimization algorithm. This itself is executed by means of a fully integrated framework for automated simulation and optimization and utilizes a genetic algorithm. The presented design optimization example and approach emphasize the complexity of the optimization problem and lead to the recommendation to consider safety factors for other more critical and design-driving performance criteria. For the applied methodology and conditions it is shown that the required material for an advanced spar-type platform supporting an offshore wind turbine can be reduced by more than 31% and, at the same time, the performance of the floating system - expressed by the maximum system inclination, maximum tower top acceleration, and mean translational motion - improved in some respect.

15 *Copyright statement.* TEXT

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**Abbreviations:** AEP, Annual Energy Production; ALPSO, Augmented Lagrangian Particle Swarm Optimization; BC, Base Column; BC<sub>low</sub>, Base Column lower part; BC<sub>mid</sub>, Base Column middle part; BC<sub>up</sub>, Base Column upper part; CapEx, Capital Expenditure; COBYLA, Constrained Optimization BY Linear Approximation; DLC, Design Load Case; DNV GL, Det Norske Veritas and Germanischer Lloyd; Dymola, Dynamic Modeling Laboratory; IEC, International Electrotechnical Commission; IWES, Institute for Wind Energy Systems; LCoE, Levelized Cost of Energy; MoWiT, Modelica for Wind Turbines; NREL, National Renewable Energy Laboratory; NSGAI, Non-dominated Sorting Genetic Algorithm II; NSGAI, Non-dominated Sorting Genetic Algorithm III; OC3, Offshore Code Comparison Collaboration; OC4, Offshore Code Comparison Collaboration Continuation; OpEx, Operational Expenditure; Rkfix4, Runge-Kutta fixed-step and 4th order method; SPEA2, Strength Pareto Evolutionary Algorithm 2; SWL, Still Water Level; TI, Turbulence Intensity; TP, Tapered Part; UC, Upper Column

## 1 Introduction

With floating support structures for offshore wind turbines, more offshore wind resources can be captured and used for power generation, as around 60% to 80% of the ocean areas cannot be exploited with bottom-fixed structures, which are limited to water depths of up to around 50 m (European Wind Energy Association, 2013). The floating offshore wind technology is no longer in its infancy. Over the last decade, the technology readiness level of floating offshore wind turbine systems has significantly increased so that “floating offshore wind is coming of age”, as WindEurope states in its floating offshore wind vision statement (WindEurope, 2017, p.4). The large number of research studies, research projects, scaled model tests, prototype developments, and full scale model test phases paved the way towards this current status. More than 30 floating foundation concepts exist and are under development (Quest Floating Wind Energy, 2020; Future Power Technology, 2019; James and Ros, 2015; Mast et al., 2015). A few selected milestones are (Löfken, 2019)

- the Hywind spar-buoy floating system, with a 2.3 MW demonstrator deployed in 2009, the subsequent Hywind Scotland pilot park of five 6 MW turbines operating since 2017, and another wind farm Hywind Tampen with eleven 8 MW turbines planned for 2022;
- the WindFloat semi-submersible floating system by Principle Power, with three 2 MW demonstrators since 2011 and twelve large projects planned for the upcoming years with turbines of up to 8.4 MW;
- the Damping Pool<sup>®</sup> (Floatgen) barge floating system by Ideol, with a 2 MW and a 3 MW demonstrator since 2018 and further large projects with for example 6.2 MW wind turbines planned for the future; and
- the TetraSpar spar, semi-submersible, or tension leg platform floating system by Stiesdal Offshore Technologies, with a demonstrator supporting a 3.6 MW wind turbine planned for spring 2020.

Despite the great amount of floating offshore wind projects, most of them are under development and currently the Hywind Scotland pilot park is the one and only operational floating wind farm (Future Power Technology, 2019), **apart from the first prototype floating wind farm within the Fukushima Floating Offshore Wind Farm Demonstration Project FORWARD, in which three different floating wind turbines connected to the same floating substation are tested for a limited operating life** (James and Ros, 2015; Main(e) International Consulting LLC, 2013). More are planned as already mentioned above; however, for further speed-up of the market uptake of floating offshore wind farms, significant cost-reductions are still required. From the survey-based study by Leimeister et al. (2018) the conclusion is drawn that the spar-buoy concept is the most mature and has the highest technology readiness level. However, in order to enhance its suitability for multi-MW wind farm deployment, this technology has to be further advanced: the common spar-buoy floater is already very convenient for volume production and certification due to its simple geometry, but to facilitate an accelerated and global market uptake, especially the large floater draft has to be reduced, so that in the end the levelized cost of energy (LCoE) is reduced and the handling simplified.

To overcome the challenges that the highly promising spar-buoy floating platform type still faces, a few researchers have already worked on concepts for **advanced** spar-type floating offshore wind turbine support structures, which have a reduced draft

but still provide sufficient stability (Wright et al., 2019; Yoshimoto and Kamizawa, 2019; Zhu et al., 2019; Hirai et al., 2018; Yoshimoto et al., 2018; Yamanaka et al., 2017; Matsuoka and Yoshimoto, 2015; Lee, 2005). However, different approaches for designing the floating platform are followed and it does not seem that a fully integrated optimization approach is adopted. Other design development studies (Chen et al., 2017; Perry et al., 2007; Bangs et al., 2002) are inspired by the oil and gas industry and deal with so-called truss spar platforms, in which a truss section connects a bottom tank with the floating platform and heave plates can be included. However, only Perry et al. (2007) apply a genetic algorithm based optimization for developing a cost-efficient preliminary floating support structure design. Some other researchers focus on the optimization of the dynamic response of the floating offshore wind turbine system by rather adding and optimizing additional components instead of the spar-type structure itself. Hence, Ding et al. (2017b, a) use helical strakes - again inspired by the oil and gas industry - and a heave plate, while He et al. (2019) optimize a tuned mass damper by utilizing an artificial fish swarm algorithm. Pham and Shin (2019) add a moonpool, which is optimized together with the commonly shaped spar-type platform, following a three-step and, hence, no integrated optimization approach. The majority of design optimization approaches, however, is based on the common spar-type floater shape and utilizes gradient-based methods (Hegseth et al., 2020; Berthelsen et al., 2012; Fylling and Berthelsen, 2011) or genetic algorithms (Karimi et al., 2017; Choi et al., 2014). Some applications are purely dealing with the support structure - focusing on basic hydrodynamic analyses, maximum system stability, and minimum material cost (Choi et al., 2014), reduced draft, weight, and cost with at the same time increased power output (Lee et al., 2015), or optimized floater cost and power generation (Gao and Sweetman, 2018) - while other design optimization approaches are highly complex and account for optimizing several components of the floating wind turbine system, such as the tower, mooring system, power cable, and/or blade-pitch controller in addition to the floating platform, and focus on extreme loads, structural strength, fatigue life, or power quality in addition to costs and global system responses (Hegseth et al., 2020; Sandner et al., 2014; Fylling and Berthelsen, 2011) or distinguish also between different floater types (Karimi et al., 2017; Sclavounos et al., 2008). Even if a reduced draft is often aimed and obtained (Hegseth et al., 2020; Gao and Sweetman, 2018; Lee et al., 2015; Sandner et al., 2014) and sometimes the spar-buoy floater is subdivided into several cylindrical sections (Hegseth et al., 2020; Berthelsen et al., 2012; Fylling and Berthelsen, 2011) or a broad range of allowable values is considered for the design variables (Karimi et al., 2017; Sclavounos et al., 2008), always common spar-type platform designs are considered, meaning a structure consisting of welded sections, for which reason even Hegseth et al. (2020) limit the maximum allowable taper angle. Thus, the aim of this paper is to demonstrate that, through a more comprehensive fully integrated design optimization approach and by allowing design variables out of a wider range of values, more potential solutions for an advanced spar-type floater design can be captured. Apart from reducing the floater draft, the main objective is cost reduction - expressed in terms of the material used - while global system performance criteria have to be fulfilled. All these requirements regarding design variables and optimization criteria are - together with specific environmental conditions and the fully-coupled aero-hydro-servo-elastic dynamic characteristics of a floating offshore wind turbine system - incorporated into a fully integrated optimization framework. By means of this, an advanced spar-type floating offshore wind turbine support structure design is aimed to be obtained. The focus of the optimization procedure lies on hydrodynamic and system-level analyses and not that stringent limitations on the

**structure and dimensions are required.** This way and by considering different structural realization approaches for the resulting optimized geometries, new alternatives of potential and innovative floater design solutions are opened up.

In order to figure out in detail the required characteristics of such a floating platform, first, advanced spar-type floating wind turbine support structures are elaborated in detail in Sect. 2 and a reference floating system with corresponding assessment criteria is specified. Based on this, the optimization problem - consisting of design variables, objective function, and constraints - is defined in Sect. 3. Subsequently, the automated design optimization of the advanced spar-type floating wind turbine system is performed in Sect. 4, including some preprocessing automated design load case (DLC) simulations, as well as the characterization of the automated optimization framework and the iterative optimization approach. The results of the optimization simulations are presented in Sect. 5 and further discussed in Sect. 6. Finally, some conclusions are drawn in Sect. 7.

## **2 Advanced spar-type floating wind turbine support structures**

According to the survey conducted by Leimeister et al. (2018), industry professionals and scientific experts judge the advanced spar-type floating platform - compared to the common spar-buoy floaters, semi-submersibles, tension leg platforms, barges, or any hybrid, multi-turbine, or mixed-energy floating system - to be the most suitable support structure for wind turbines to be deployed in floating offshore wind farms due to their suitability for serial production, possibility of receiving certification, low LCoE, and little demands on the mooring system.

### **2.1 Characteristics of advanced spar-type floaters**

The common spar-buoy floating platform consists of a long relatively slender cylinder which is filled at the bottom end with ballast. The resulting deep center of gravity provides stability against overturning. However, this floating system exhibits some weaknesses: due to its deep draft it cannot be deployed in shallow or intermediate waters up to around 100 m (James and Ros, 2015), nor can the entire floating wind turbine system be fully assembled in upright position onshore or at harbor sites. The latter fact adds to the already expensive floater, as it makes the overall handling of this long and heavy structure, its assembly, transport, and installation costly. Thus, by

- reducing the draft,
- applying a delta or so called crowfoot connection of the mooring lines to the spar-buoy structure, and/or
- adding damping fins,

the advanced spar-type floating system can benefit from

- a wider range of possible installation sites,
- simplified handling (both construction, assembly, transport, and installation),
- reduced system, as well as construction and transportation costs, as well as

– improved system motion performance. (Leimeister et al., 2018)

In particular, these characteristics of advanced spar-type floating platforms are realized in a few - both research and real - concepts. The advanced spar-type floater by the Massachusetts Institute of Technology (Lee, 2005) has a relatively shallow draft and gets stability support from a two-layered taut-leg mooring system (Butterfield et al., 2007). Both Hirai et al. (2018) and Yamanaka et al. (2017) use a three-segmented advanced geometry spar, where a larger diameter column makes up the middle part to allow for shortening the overall length of the spar and reducing the system cost, while Zhu et al. (2019) utilize the three elements just in an opposite way, focusing on increased restoring and improved motion performance: the spar element makes up the middle part and interconnects two columns, one with just a slightly larger diameter at the bottom end and another one with a large diameter at the upper end.

Within the Fukushima Floating Offshore Wind Farm Demonstration Project FORWARD an advanced spar-type support structure, developed by Japan Marine United, is utilized for a floating substation (Fukushima Kizuna) and a 5 MW wind turbine (Fukushima Hamakaze) (Yoshimoto and Kamizawa, 2019; James and Ros, 2015; Main(e) International Consulting LLC, 2013). The advanced spar for the floating substation consists of three columns - or so called hulls - placed at the bottom, in the middle, and at the upper end (intersecting the water line) of the spar, so that the floating system is suitable already at around 110 m water depth, the motion performance is improved, and the cost for installation is reduced (Wright et al., 2019; Yoshimoto et al., 2018; Matsuoka and Yoshimoto, 2015). The Fukushima Hamakaze was initially using a similarly structured advanced spar, equipped with damping fins for stabilization in sway and heave direction (James and Ros, 2015; Main(e) International Consulting LLC, 2013); however, after some investigations and studies by Matsuoka and Yoshimoto (2015), finally the advanced spar-type platform for the 5 MW wind turbine consists of just two large columns/hulls at the bottom and top end of the spar and, thus, is optimized with respect to the system restoring and motion performance, as well as the construction cost (Yoshimoto and Kamizawa, 2019). Despite these optimizations, the installation of the floating platform - in particular the ballasting operations - turned out to be complex, as the floater has leaned to an angle of 45° when it was brought from the construction draft to a deeper draft, which, however, could be resolved within less than a week (JWPA, 2017; Foster, 2016).

## 2.2 Reference floating offshore wind turbine system

As starting point of the design optimization towards an advanced spar-type floating platform for an offshore wind turbine, a traditional spar-buoy floating wind turbine system, taken from phase IV of the OC3 (Offshore Code Comparison Collaboration) project (Jonkman, 2010), is used and modified, as explained in Sect. 2.3, to allow the development of an advanced spar-type structure.

The OC3 phase IV floating offshore wind turbine system consists of

– the NREL (National Renewable Energy Laboratory) 5 MW reference wind turbine (Jonkman et al., 2009) with a rotor diameter of 126.0 m, a hub height of 90.0 m, an overall mass of the rotor-nacelle assembly of 350,000 kg, and an operating range between 3.0 m/s and 25.0 m/s with rated wind speed at 11.4 m/s;

- 145 – an offshore adapted tower (Jonkman, 2010) ranging from 10.0 m elevation above still water level (SWL) up to 87.6 m, which is tapered from a diameter and wall thickness of 6.5 m and 0.027 m, respectively, at the base to a diameter and wall thickness of 3.87 m and 0.019 m, respectively, at the top and weighs 249,718 kg;
- the spar-buoy floater (Jonkman, 2010) with a top diameter of 6.5 m at 10.0 m elevation above SWL, which increases between 4.0 m below SWL and 12.0 m below SWL up to 9.4 m, which corresponds to the diameter at the base at 120.0 m below SWL, and an overall mass - including ballast - of 7,466,330 kg; and
- 150 – three evenly spaced catenary mooring lines of 902.2 m length each and 0.09 m diameter, which are attached to the spar-buoy at 70.0 m below SWL and anchored to the seabed at 320.0 m water depth in a radius of 853.87 m from the floater centerline (Jonkman, 2010).

### 2.3 Modifications for defining an advanced spar-type floater

An aero-hydro-servo-elastic coupled model of dynamics for this original OC3 phase IV spar-buoy floating wind turbine system is developed and verified by Leimeister et al. (2020a), using the MoWiT (Modelica for Wind Turbines) library (Leimeister and Thomas, 2017; Thomas et al., 2014; Strobel et al., 2011). The modeling approach in MoWiT utilizes the object-oriented, equation-based, and component-based modeling language Modelica<sup>1</sup> and therefore follows a hierarchical structure with interconnected main components and subcomponents to represent the complex wind turbine system and fully-coupled system dynamics. This multibody approach provides high flexibility to model various wind turbine system types, environmental conditions, and simulation settings by simply modifying single model components. The MoWiT library, developed at Fraunhofer IWES (Institute for Wind Energy Systems), is continuously enhanced and more features and interfaces are added, which opens up a broad application range, including the integration into a framework for automated simulation and optimization, as utilized in this study. (Leimeister et al., 2020b)

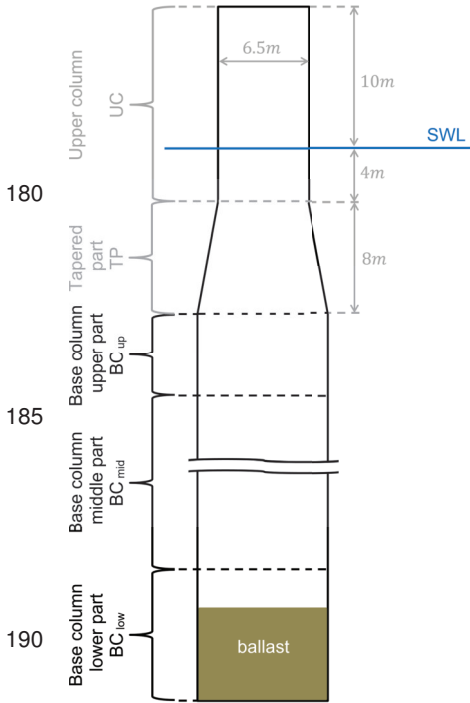
This MoWiT model of the OC3 phase IV spar-buoy floating wind turbine system is used as basis and modified so that a design of an advanced spar-type floater can be obtained through automated optimization. As this work focuses on the design of the floating platform and not on the mooring system, a shorter, less heavy, and, hence, cheaper advanced spar-type floater design shall be obtained by changing the floater geometry. Different characteristic shapes of advanced spar-type floating platforms are pointed out in Sect. 2.1. In this study, a similar concept as presented by Zhu et al. (2019) and realized in the Fukushima Hamakaze floating wind turbine system (Matsuoka and Yoshimoto, 2015; Yoshimoto and Kamizawa, 2019) is applied: the long cylindrical element below the tapered part is divided into three partitions:

1. the base column upper part  $BC_{up}$ , which shall serve for gaining buoyancy;
2. the base column middle part  $BC_{mid}$ , which mainly provides the separation of parts 1 and 3 to deepen the position of part 3; and

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<sup>1</sup><https://www.modelica.org/> (Accessed: 22 January 2020)

175 3. the base column lower part  $BC_{low}$ , which can be filled with ballast and this way shall shift the center of gravity downwards.



**Figure 1.** Geometrical definitions of the advanced spar-type floating platform.

195 structure<sup>2</sup> is changed from the fixed value of 0.0314 m, which is derived by Leimeister et al. (2020a), to a wall thickness that is adaptable to the specific advanced spar-type floater design. In order to obtain an appropriate wall thickness for a corresponding floater design, a fixed ratio of the support structure structural mass to the displaced mass of water is deployed, which is for a spar-type floating platform 0.13 - according to representative values from research designs and academic studies and excluding designs, such as the Hywind demonstrator, which are for safety reasons heavily oversized (Bachynski, 2018). Hence, 200 the equivalent structural mass of the advanced spar-type floater (meaning the mass of the advanced spar-type steel structure excluding the tower and wind turbine, and as well excluding the ballast mass) with certain outer dimensions (diameters  $D_i$  and heights  $H_i$ ) and corresponding displaced volume can be determined following Eq. (1).

$$\frac{\text{spar structural mass}}{\text{buoyancy mass}} = 0.13 \quad (1)$$

<sup>2</sup>Referring here purely to the circumferential walls of the hollow cylindrical or conical elements, as for base and lid a fixed marginal cap thickness of 0.001 m is applied, according to the implemented model in the verification study (Leimeister et al., 2020a).

205 With the resulting structural mass of the advanced spar-type floater of 1.070E+06 kg, which is a bit lower than the original structural mass of 1.150E+06 kg (Leimeister et al., 2020c), the corresponding appropriate wall thickness, which is kept the same and constant for all parts of the specific advanced **geometry** spar design, is computed by means of Eq. (2), which is derived from the expression for the mass of the advanced **geometry** spar steel structure with a material density of 7,850 kg/m<sup>3</sup> as explained above. In Eq. (2),  $H_i$  and  $D_i$  are the heights and diameters of each element, meaning UC, TP, BC<sub>up</sub>, BC<sub>mid</sub>, and 210 BC<sub>low</sub>, while the diameter of the tapered part  $D_{TP}$  is determined according to Eq. (3) as mean of the diameters of UC and BC<sub>up</sub>.

$$\text{wall thickness} = \frac{\sum_i (H_i D_i) - \sqrt{[\sum_i (H_i D_i)]^2 - \frac{4}{\pi} \frac{\text{spar structural mass}}{\text{material density}} \sum_i H_i}}{2 \sum_i H_i} \quad (2)$$

$$D_{TP} = \frac{D_{UC} + D_{BC,up}}{2} \quad (3)$$

This way, a wall thickness of 0.0372 m is obtained for the original OC3 phase IV spar-buoy with reduced material density 215 (7,850 kg/m<sup>3</sup>) and adopted structural mass to displaced mass ratio of 0.13. This wall thickness value lies within the acceptable range, based on available data for the semi-submersible floating platform from phase II of OC4 (Offshore Code Comparison Collaboration Continuation).

As the advanced spar-type floater design (optimization) study does not focus on the mooring system, as mentioned above and due to the fact that the mooring system itself could be covered in a separate optimization task, any change in the restoring 220 system characteristics due to shifted fairlead positions is prevented by utilizing constant (the original) resulting mooring system properties. This means that - independent of possible attachment points to the reshaped floating platform - the resulting stiffness **of each mooring line** is taken from the system motion, assuming the original fairlead positions as defined in Sect. 2.2. **A realistic mooring system design for the finally obtained optimized floating platform, which represents the considered resulting mooring system properties, can then afterwards be obtained through a subsequent optimization, which might even be manual** 225 **- depending on the degree of complexity - as it is applied in studies for designing equivalent mooring systems** (Molins et al., 2015; Udoh, 2014). **However, having not included the mooring system as design variable within the optimization of the floating spar-type platform, further system performance improvements due to modified mooring system parameters or fairlead positions - in addition to an optimized support structure design - are limited. This, however, leaves open the possibility of subsequent fine tuning of the design solution obtained through optimization based on hydrodynamic and system-level analyses. By addressing** 230 **the mooring system in a successive but separate optimization algorithm, the dynamic response of the floating offshore wind turbine system, as well as the mooring line tension itself, can be significantly improved by considering an advanced and more complex optimization problem, in which - apart from various line diameters and lengths - different mooring line arrangements and distribution forms can be utilized, the optimum number of lines within the mooring system and best fairlead position elaborated, different mooring types used or even mixed within segmented lines, and also clump weights incorporated** (Tafazzoli 235 et al., 2020; Barbanti et al., 2019; Men et al., 2019; Chen et al., 2017).



## 2.4 Assessment criteria for designing an optimized advanced spar-type floater

The focus in this study lies on obtaining an advanced spar-type floating platform, which is characterized through a limited draft and reduced structural cost, but still shows good hydrodynamic performance. Any detailed structural integrity checks are not addressed in this work, but can be added for a more extensive optimization approach. However, by focusing only on hydro-  
 240 dynamics and global system performance without defining any restrictions regarding structural aspects, floater designs, which would have been discarded when performing structural integrity checks and as they would be unfeasible to be realized with conventional structural approaches, can still be captured as potential solutions when considering different structural realization approaches.

The only structural related focus, considered in this approach, is the minimization of the structural cost. This is represented  
 245 through the steel volume of the floater, which is finally specified as objective of the optimization problem, as formally declared in Sect. 3.2.

In order to achieve the shortened length of the advanced spar-type floater, the allowable draft of the system is limited to the original draft of the OC3 phase IV floating wind turbine system as maximum value, as well as to a recommended minimum value of 15.0 m (Ng and Ran, 2016). The resulting allowable total height of the BC has to be distributed to the three partitions.  
 250 As, however, this distribution is not restricted, keeping also the option of utilizing not all three BC parts, the minimum allowable value for the height of each of the BC parts is machine epsilon ( $10^{-15}$  m) - as a zero value is unfeasible from a modeling point of view. For the ballast height, it additionally has to be guaranteed that it does not exceed the actual  $BC_{low}$  height. The resulting allowable value ranges based on the draft limits are summarized in Table 1.

**Table 1.** Allowable value ranges addressing the draft limits.

	Allowable draft	Resulting total height of BC	$BC_{up}$ height	$BC_{mid}$ height	$BC_{low}$ height	Ballast height
<b>Min</b>	15.0 m	3.0 m	$10^{-15}$ m	$10^{-15}$ m	$10^{-15}$ m	$10^{-15}$ m
<b>Max</b>	120.0 m	108.0 m	108.0 m	108.0 m	108.0 m	108.0 m

The applied concept of a three-segmented advanced spar-type floater with elements for buoyancy, distance, and ballast  
 255 shall not only allow different heights but also different diameters of these elements. Thus, the allowable value range for the diameter of each of the BC parts is set from machine epsilon - due to the same modeling feasibility reason - to 120.0 m. The maximum diameter is chosen deliberately large - corresponding to the total maximum draft of the floating system - to ensure that the border of feasible solutions is well captured. From the manufacturing point of view, cylindrical offshore structures with diameters of more than 10.0 m are realistic: various sources<sup>3,4</sup> state a value of 11.0 m, the reference semi-submersible  
 260 floating platform from phase II of OC4 has an upper column diameter of 12.0 m (Robertson et al., 2014), and the diameter

<sup>3</sup><https://sif-group.com/en/wind/foundations> (Accessed: 13 August 2019)

<sup>4</sup><https://www.windkraft-journal.de/2019/06/14/steelwind-nordenham-ist-von-wpd-die-gruendungsstrukturen-fuer-den-offshore-wind-park-yunlin-in-taiwan-zu-fertigen/136551> (Accessed: 13 August 2019)

of the spar-buoy utilized in the Hywind Scotland floating wind farm<sup>5,6</sup> is even up to 14.5 m large. However, looking at other floating platform solutions, such as the Damping Pool<sup>®</sup> floater by Ideol<sup>7</sup> with outer dimensions of 36 m x 36 m and a resulting diagonal length of almost 51 m or again the OC4 phase II semi-submersible platform (Robertson et al., 2014) with an overall outer dimension of almost 82 m in diameter, shows that floating structures with a large overall outer diameter can be obtained  
265 without being restricted to the manufacturing feasibility limits for pure cylinders. Thus, from a hydrodynamic point of view, a cylindrical offshore structure with very large diameter can be realized as well through several smaller diameter cylinders being clustered together in a circle, representing similar hydrodynamic behavior and characteristics. Finally, attention has to be drawn on the minimum possible diameter of the BC parts, which always has to be at least as large as twice the actual wall thickness corresponding to the specific advanced spar-type floater design.

270 Having modified the diameters and heights of the three BC parts, as well as the ballast filling height, and having adjusted the wall thickness according to the structural mass to displaced mass ratio, as defined in Sect. 2.3, the ballast density has to be adjusted to match the original floating equilibrium between buoyancy force, system weight, and downward mooring force, so that the original hub height is maintained. In order to exclude unfeasible system solutions, in which material would have to be removed from the system (realized for example by reducing the material density) to meet this equilibrium condition, it  
275 has to be ensured that the actual resulting ballast density of the specific advanced spar-type floater design carries a positive value. However, in order to account for truly realistic ballast densities, also the uppermost allowable value of the ballast density has to be constrained. Leimeister et al. (2020c) have explored within a first-stage design optimization application example densities for common and cheap materials to be used as ballast for a floating spar-buoy. The densest material included is sandstone (or other rocks) with a density of about 2.6E+03 kg/m<sup>3</sup>. Apart from sand, sand mixed with water, concrete, or rocks,  
280 MagnaDense (heavyweight concrete) is as well used in industry as high density material<sup>8,9,10</sup>. With MagnaDense densities of up to 5.0E+03 kg/m<sup>3</sup> can be obtained<sup>11</sup> (LKAB Minerals, 2019). Even if minimization of the structure material volume is defined as objective function - as stated at the beginning of this section - in order to represent the structural cost, the cost of the two potential densest ballast materials is elaborated to avoid significant larger ballast costs when utilizing MagnaDense instead of the common cheap materials pointed out by Leimeister et al. (2020c). However, when comparing the material  
285 prices for sandstone<sup>12</sup> (for the ballast density limit of 2.6E+03 kg/m<sup>3</sup>) and MagnaDense<sup>8,13</sup> (for the ballast density limit of 5.0E+03 kg/m<sup>3</sup>), it turns out that both ballast materials have a similar cost of around 150 \$ per ton, which is less than 20% of

<sup>5</sup><https://www.equinor.com/content/dam/statoil/documents/newsroom-additional-documents/news-attachments/brochure-hywind-a4.pdf> (Accessed: 13 June 2019)

<sup>6</sup><https://www.equinor.com/en/news/worlds-first-floating-wind-farm-started-production.html> (Accessed: 13 June 2019)

<sup>7</sup><https://floatgen.eu/> (Accessed: 13 August 2019)

<sup>8</sup>Floating offshore wind project manager at a leading company in offshore industry, personal communication, 6 February 2020.

<sup>9</sup><https://www.lkabminerals.com/en/industry-uses/offshore-energy/offshore-wind-structures/> (Accessed: 7 June 2020)

<sup>10</sup><https://www.lkabminerals.com/de/floating-offshore-wind-2018/> (Accessed: 7 June 2020)

<sup>11</sup><https://www.lkabminerals.com/wp-content/uploads/2019/02/MagnaDense-SDS-12-06INT-19-03.pdf> (Accessed: 5 February 2020)

<sup>12</sup><https://www.alibaba.com/showroom/sandstone-price-per-ton.html> (Accessed: 5 February 2020)

<sup>13</sup><https://german.alibaba.com/product-detail/magnadense-heavy-concrete-172429386.html> (Accessed: 5 February 2020)

the material cost for structural (raw) steel of about 700 \$ per tonne<sup>14</sup> (Grogan, 2018; Butcher, 2018). Thus, the ballast density is constrained to a maximum of 5.0E+03 kg/m<sup>3</sup>.

290 Apart from these more geometry related assessment criteria, there are three performance related criteria, which the advanced spar-type floating offshore wind turbine system has to fulfill. For the global system performance of a floating offshore wind turbine maximum allowable values are prescribed for

1. the total inclination angle of the system to the vertical:

for system rotational stability reasons a maximum total inclination angle of 10.0° is allowed in operational conditions (Leimeister et al., 2020c; Katsouris and Marina, 2016; Kolios et al., 2015; Huijs et al., 2013);

295 2. the total horizontal acceleration at the tower top:

due to sensitive components in the nacelle and to prevent any issues with the lubrication, the nacelle acceleration - corresponding to the acceleration at the tower top - is limited, depending on the specific wind turbine, to a maximum of 0.2 to 0.3 times the gravitational acceleration constant (Nejad et al., 2017; Huijs et al., 2013; Suzuki et al., 2011); herein the lower value of 1.962 m/s<sup>2</sup> is used following a conservative approach (Leimeister et al., 2020c); as well as

300 3. the mean translational motion of the floating system:

based on experience, the static translational displacement of a (non TLP-type) floating offshore wind turbine system, corresponding to the mean of the translational motion, is restricted to 0.2 times the water depth (320.0 m in the case of the OC3 phase IV spar-buoy floating system), and hence to 64.0 m in this application (Leimeister et al., 2020c).

### 3 Definition of the optimization problem

305 For obtaining an optimized advanced spar-type floater design, following the assessment criteria - as outlined in Sect. 2.4 - and using the modified floating wind turbine system model - as described in Sect. 2.3 - as basis, an iterative optimization approach (explained in more detail in Sect. 4.3) is carried out in this study. This optimization approach requires the definition of the optimization problem - comprising the modifiable design variables  $x_i$ , the objective functions  $f_i$  to be minimized, as well as the equality ( $h_i$ ) and inequality ( $g_i$ ) constraints to be fulfilled - as given in formal expressions in the following:

$$\begin{aligned}
 &\text{find} && X = \{x_1, \dots, x_k\} \\
 &\text{to minimize} && f_i(X, \text{system}(X)) \quad , \quad i = 1, \dots, l \\
 &\text{subject to} && h_i(X, \text{system}(X)) = 0 \quad , \quad i = 1, \dots, m \\
 &\text{subject to} && g_i(X, \text{system}(X)) \leq 0 \quad , \quad i = 1, \dots, n
 \end{aligned}$$

310

The functions are either directly depend on the design variables or also on the resulting fully-coupled complex floating offshore wind turbine system, denoted with  $\text{system}(X)$ .

<sup>14</sup><https://spendonhome.com/structural-steel-fabrication-cost/> (Accessed: 5 February 2020)

### 3.1 Design variables of the advanced spar-type floating wind turbine system

Based on the derivation of the modified spar-buoy floater model for enabling the design of an advanced spar-type floating platform (Sect. 2.3), the design variables vector  $X = \{x_1, x_2, \dots, x_6, x_7\}$  with the following seven ( $k = 7$ ) elements is defined:

- $x_1$ , the diameter of  $BC_{up}$ ;
- $x_2$ , the diameter of  $BC_{mid}$ ;
- $x_3$ , the diameter of  $BC_{low}$ ;
- $x_4$ , the height of  $BC_{up}$ ;
- 320 –  $x_5$ , the height of  $BC_{mid}$ ;
- $x_6$ , the height of  $BC_{low}$ ; and
- $x_7$ , the ballast height.

### 3.2 Objective function for the advanced spar-type floating wind turbine system

As stated in Sect. 2.4, just one objective function ( $l = 1$ ) is specified, which corresponds to the structure material volume of the advanced spar-type floating platform. This objective function ( $f_1$ ) is to be minimized, as defined at the beginning of Sect. 3.

### 3.3 Constraints for the advanced spar-type floating wind turbine system

Section 2.4 covers already the assessment criteria for designing an optimized advanced spar-type floating platform. These make up - apart from the objective function - 25 constraints, which are all specified as inequality constraints - hence,  $m = 0$  (for the equality constraints  $h_i$ ) and  $n = 25$  (for the inequality constraints  $g_i$ ). These shall all take on values less or equal to zero, as expressed at the beginning of Sect. 3. The definitions of the inequality constraints are listed in Table 2.

## 4 Automated design optimization of the advanced spar-type floating wind turbine system

The final automated design optimization of the reference advanced spar-type floating wind turbine system described in Sect. 2.3 consists of

1. preprocessing automated system simulations for identifying the simulation conditions to be considered within the optimization (Sect. 4.1), as well as
- 335 2. the actual iterative optimization approach for obtaining an optimized advanced spar-type floating platform design (Sect. 4.3).

Both utilize a framework for automated simulation and optimization developed at Fraunhofer IWES and presented in Sect. 4.2.

**Table 2.** Definition of the 25 inequality constraints.

Inequality constraint	Formal expression	Description
$g_1$	$10^{-15} \text{ m} - x_1$	Allowable value range of $x_1$
$g_2$	$x_1 - 120.0 \text{ m}$	Allowable value range of $x_1$
$g_3$	$10^{-15} \text{ m} - x_2$	Allowable value range of $x_2$
$g_4$	$x_2 - 120.0 \text{ m}$	Allowable value range of $x_2$
$g_5$	$10^{-15} \text{ m} - x_3$	Allowable value range of $x_3$
$g_6$	$x_3 - 120.0 \text{ m}$	Allowable value range of $x_3$
$g_7$	$10^{-15} \text{ m} - x_4$	Allowable value range of $x_4$
$g_8$	$x_4 - 108.0 \text{ m}$	Allowable value range of $x_4$
$g_9$	$10^{-15} \text{ m} - x_5$	Allowable value range of $x_5$
$g_{10}$	$x_5 - 108.0 \text{ m}$	Allowable value range of $x_5$
$g_{11}$	$10^{-15} \text{ m} - x_6$	Allowable value range of $x_6$
$g_{12}$	$x_6 - 108.0 \text{ m}$	Allowable value range of $x_6$
$g_{13}$	$10^{-15} \text{ m} - x_7$	Allowable value range of $x_7$
$g_{14}$	$x_7 - 108.0 \text{ m}$	Allowable value range of $x_7$
$g_{15}$	$\max(\text{total inclination angle}) - 10.0^\circ$	Maximum total inclination angle
$g_{16}$	$\max(\text{horizontal nacelle acceleration}) - 1.962 \text{ m/s}^2$	Maximum horizontal nacelle acceleration
$g_{17}$	$\text{mean}(\text{translational motion}) - 64.0 \text{ m}$	Mean translational motion
$g_{18}$	$3.0 \text{ m} - (x_4 + x_5 + x_6)$	Minimum draft
$g_{19}$	$x_4 + x_5 + x_6 - 108.0 \text{ m}$	Maximum draft
$g_{20}$	$x_7 - x_6$	Ballast filling height within $\text{BC}_{\text{low}}$
$g_{21}$	$-\text{ballast density}$	Allowable value range of the ballast density
$g_{22}$	$\text{ballast density} - 5.0\text{E}+03 \text{ kg/m}^3$	Allowable value range of the ballast density
$g_{23}$	$0.5 \cdot 10^{-15} \text{ m} + \text{wall thickness} - 0.5x_1$	Wall thickness and diameter of $\text{BC}_{\text{up}}$
$g_{24}$	$0.5 \cdot 10^{-15} \text{ m} + \text{wall thickness} - 0.5x_2$	Wall thickness and diameter of $\text{BC}_{\text{mid}}$
$g_{25}$	$0.5 \cdot 10^{-15} \text{ m} + \text{wall thickness} - 0.5x_3$	Wall thickness and diameter of $\text{BC}_{\text{low}}$

#### 4.1 Preprocessing automated system simulations

Standardization and classification bodies, such as IEC (International Electrotechnical Commission) and DNV GL (Det Norske  
340 Veritas and Germanischer Lloyd), give recommendations on DLCs to be considered when designing floating offshore wind turbine systems. Thus, in the technical specification IEC TS 61400-3-2 (International Electrotechnical Commission, 2019b), based on the international standard IEC 61400-3-1 (International Electrotechnical Commission, 2019a), and in the standard DNVGL-ST-0119 (DNV GL AS, 2018), building on the standard DNVGL-ST-0437 (DNV GL AS, 2016), a substantial number of DLCs is listed which cover different operating states at various environmental conditions. When performing an iterative

345 design optimization approach, however, it is not practical to simulate the full set of DLCs for each design considered within the iterative optimization approach. This is not only for reasons of high computational effort, but also due to the fact that not all DLCs may be relevant or design driving for the specified optimization problem.

Thus, in this work, the same approach as taken by Leimeister et al. (2020c) in another design optimization application example is adopted. In this, first, a limited number of DLCs, critical for the considered floating offshore wind turbine system and design optimization problem, is selected - a common approach in research studies (Leimeister et al., 2020c; Krieger et al., 350 2015; Matha et al., 2014; Huijs et al., 2013; Bachynski et al., 2013; Bachynski and Moan, 2012; Suzuki et al., 2011). For the considered advanced spar-type floating offshore wind turbine system, described in Sect. 2, and the corresponding optimization problem stated in Sect. 3, three DLCs according to IEC 61400-3-1 (International Electrotechnical Commission, 2019a) are selected (Leimeister et al., 2020c):

- 355 – DLC 1.1 around rated wind speed (explicitly at 10.0 m/s, 11.4 m/s, and 13.0 m/s), as well as
- DLC 1.3 and
- DLC 1.6, both at 8.0 m/s, 11.4 m/s (rated wind speed), and 25.0 m/s (cut-out wind speed).

These are chosen to cover highest thrust loads and corresponding system inclination and mean translational displacement at rated wind speeds, as well as maximum dynamic responses in extreme turbulent wind conditions or at severe irregular sea 360 states, as the maximum total inclination angle, the maximum horizontal nacelle acceleration, and the mean translational motion make up three ( $g_{15}$ ,  $g_{16}$ , and  $g_{17}$ ) of the optimization constraints defined in Sect. 3.3, which need to be checked and adhered to.

From these selected three DLCs, 54 environmental conditions are defined, which correspond to 18 different environmental settings per DLC as summarized in Table 3. Thus, in each DLC turbulent wind with three different mean wind speeds and corresponding longitudinal turbulence intensity (TI) are considered. Per wind speed six different wind seed numbers are accounted 365 to capture the randomness of turbulent wind. Three different yaw misalignment angles are used and combined with two seeds each to reduce the overall number of simulation cases. The irregular sea state, prevailing in all three DLCs, is specified through the significant wave height and peak period. Furthermore, each realization of the turbulent wind with a different wind seed uses as well a different wave seed to represent again the randomness of irregular waves. Finally, a current speed is specified for each wind speed.

370 These 54 system simulations have already been performed by Leimeister et al. (2020c) with the original OC3 spar-buoy floating offshore wind turbine system and are in this study carried out with the modified reference floating system from Sect. 2.3. The simulations are executed automatically, utilizing the framework for automated simulation and optimization, which is introduced in Sect. 4.2 in more detail.

From the total simulation time of 800 s, the last 600 s (excluding any transients at the beginning) are evaluated with respect 375 to the system performance criteria. The results, presented by Leimeister et al. (2020c), show that DLC 1.6 at rated wind speed (11.4 m/s) with wind seed number 11 and yaw misalignment angle of  $8^\circ$  is most critical for the total inclination angle of the system and yields the second highest value (just less than 1% lower than the maximum value obtained from all DLCs) for the

**Table 3.** System parameters for preprocessing simulations of selected DLCs (Leimeister et al., 2020c).

DLC	Wind conditions				Sea conditions*		
	Wind speed	Long. TI	Wind seed	Yaw misalignment	Sign. wave height	Peak period	Current speed
1.1	10.0 m/s	18.34%	1 ... 6	-8°, 0°, 8°	1.74 m	6.03 s	0.074 m/s
	11.4 m/s	17.38%	7 ... 12	-8°, 0°, 8°	1.99 m	6.44 s	0.084 m/s
	13.0 m/s	16.53%	13 ... 18	-8°, 0°, 8°	2.30 m	6.92 s	0.096 m/s
1.3	8.0 m/s	35.00%	1 ... 6	-8°, 0°, 8°	1.44 m	5.48 s	0.059 m/s
	11.4 m/s	26.97%	7 ... 12	-8°, 0°, 8°	1.99 m	6.44 s	0.084 m/s
	25.0 m/s	16.68%	13 ... 18	-8°, 0°, 8°	4.94 m	10.14 s	0.184 m/s
1.6	8.0 m/s	20.30%	1 ... 6	-8°, 0°, 8°	10.37 m	14.70 s	0.059 m/s
	11.4 m/s	17.38%	7 ... 12	-8°, 0°, 8°	10.37 m	14.70 s	0.084 m/s
	25.0 m/s	13.64%	13 ... 18	-8°, 0°, 8°	10.37 m	14.70 s	0.184 m/s

\* Please notice that each realization of the turbulent wind with a different wind seed uses as well a different wave seed.

horizontal nacelle acceleration. The mean translational motion is in general far off the limit value and is just less than 3.5% of the overall maximum value for the above mentioned critical DLC. For the modified advanced spar-type floating system, the five highest values for the three performance parameters and corresponding DLC simulation cases, as well as the position of the above described most critical DLC for the original OC3 phase IV floating wind turbine system are presented in Table 4. This shows that DLC 1.6 at rated wind speed with wind seed number 11 and yaw misalignment angle of 8° is still of high criticality for the modified reference advanced spar-type floating system. It scores not the highest for the performance criteria; however, the total inclination angle of the system is almost 96% of the highest value obtained in the 54 DLC simulations, the horizontal nacelle acceleration is even almost 99% of the highest value occurring, and the mean translational motion is just less than 1% lower than the maximum value obtained.

Thus, this DLC (1.6 at 11.4 m/s wind speed with wind seed number 11 and yaw misalignment angle of 8°) is used - as already deployed in the other first-stage design optimization application example (Leimeister et al., 2020c) - for defining the environmental conditions for the system simulations throughout the subsequent iterative optimization approach, which is specified in detail in Sect. 4.3. As, however, it is not ensured that the outcome of the DLC results comparison - based on the reference advanced spar-type floating wind turbine system - does not change for the optimized floater design, the 54 environmental conditions will be simulated subsequent to the design optimization process and the criticality of the DLCs will be assessed again, as covered in Sect. 5.4.

**Table 4.** The highest values for the three performance parameters and corresponding DLC simulation case, based on the modified reference advanced spar-type floating system.

Position	DLC	Wind speed	Wind seed	Yaw misalignment	Max(total inclination angle)
1	1.6	11.4 m/s	8	-8°	3.924°
2	1.6	11.4 m/s	10	0°	3.876°
3	1.6	11.4 m/s	7	-8°	3.859°
4	1.6	11.4 m/s	11	8°	3.761°
5	1.6	11.4 m/s	12	8°	3.632°

Position	DLC	Wind speed	Wind seed	Yaw misalignment	Max(horizontal nacelle acceleration)
1	1.6	25.0 m/s	16	0°	2.339 m/s <sup>2</sup>
2	1.6	25.0 m/s	14	-8°	2.322 m/s <sup>2</sup>
3	1.6	8.0 m/s	5	8°	2.313 m/s <sup>2</sup>
4	1.6	11.4 m/s	7	-8°	2.312 m/s <sup>2</sup>
5	1.6	11.4 m/s	11	8°	2.311 m/s <sup>2</sup>

Position	DLC	Wind speed	Wind seed	Yaw misalignment	Mean(translational motion)
1	1.6	11.4 m/s	9	0°	19.533 m
2	1.1	11.4 m/s	9	0°	19.455 m
3	1.3	11.4 m/s	9	0°	19.455 m
4	1.6	11.4 m/s	12	8°	19.430 m
5	1.6	11.4 m/s	8	-8°	19.351 m
6	1.6	11.4 m/s	11	8°	19.345 m

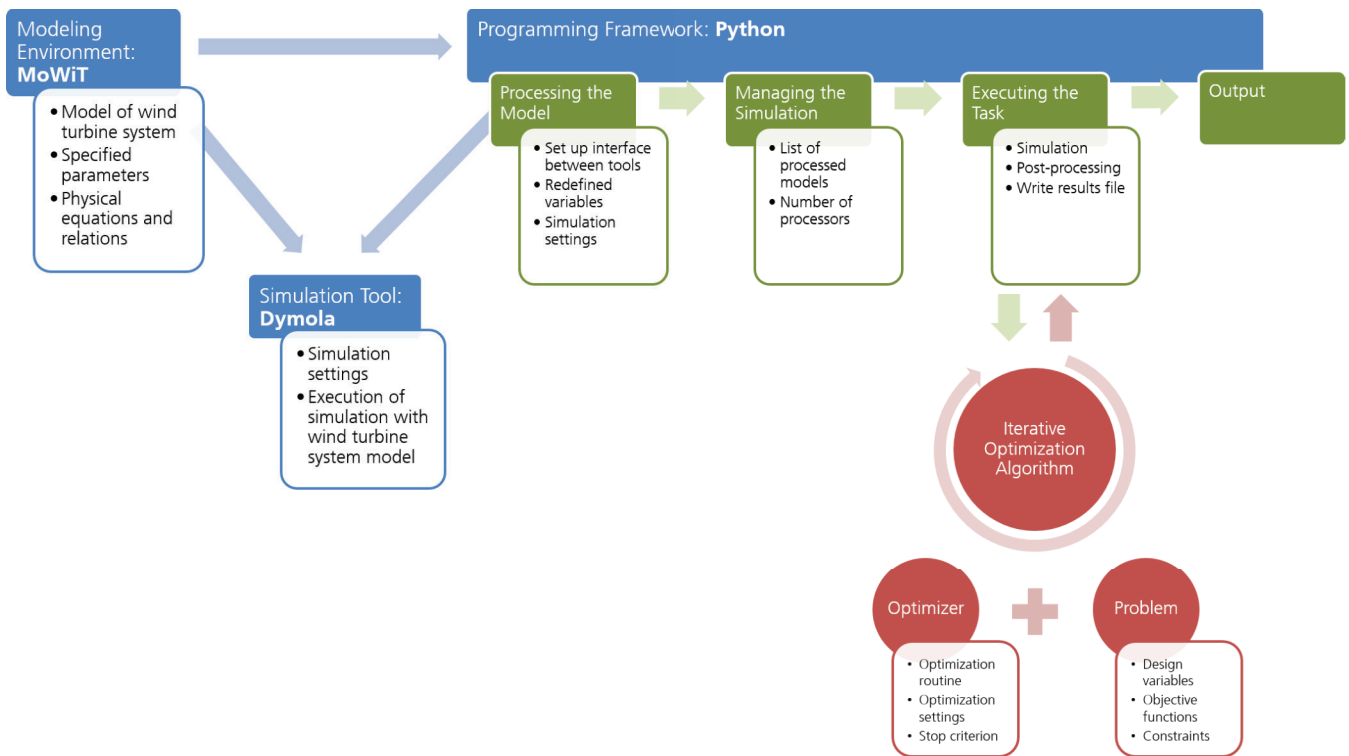
## 4.2 Automated optimization framework

395 The preprocessing DLC simulations mentioned in Sect. 4.1, as well as the actual iterative optimization approach covered in Sect. 4.3 are executed in an automated manner by means of a Python-Modelica framework for automated simulation and optimization developed at Fraunhofer IWES (Leimeister et al., 2020b, 2019).

The structure and components of this framework are presented in Fig. 2. The framework consists of three modules: a modeling environment, a simulation tool, and a programming framework.

400 1. The modeling environment is the MoWiT library, which is already introduced in Sect. 2.3. By means of the component-based MoWiT library a computational model for fully-coupled aero-hydro-servo-elastic wind turbine load calculations of the system of interest (any state-of-the-art onshore or offshore (bottom-fixed or floating) wind turbine - in this study





**Figure 2.** The Python-Modelica framework for automated simulation and optimization, adapted from Leimeister et al. (2020b).

the advanced spar-type floating offshore wind turbine system described in Sects. 2.2 and 2.3) is programmed in the open-source object-oriented and equation-based modeling language Modelica. Thus, system and environmental parameters, as well as the underlying physical equations and relations are specified. From the aero-, hydro-, control, and structural dynamic approaches available within the MoWiT library and covered in detail by Leimeister et al. (2020a), blade-element-momentum theory including dynamic stall and dynamic wake; linear Airy wave theory, Wheeler stretching, and MacCamy-Fuchs approach; built-in operating control; as well as modal reduced anisotropic beams for blades and rigid bodies for tower and floating structure are utilized in this application.

2. Dymola (Dynamic Modeling Laboratory) by Dassault Systèmes<sup>15</sup>, capable of time-domain simulations of complex Modelica models, is used as simulation tool. Herein, simulation and output intervals, integration settings, such as solver type, fixed integrator step size, or tolerance, as well as further specifications for translation, output, and debugging are defined.

3. The programming framework is developed in Python. The implemented scripts follow a four-step process. First, the interface between the three modules is established so that the provided wind turbine system model can be processed and new values can be assigned to system variables and simulation settings. This is for example done based on additional

<sup>15</sup><http://www.dymola.com/> (Accessed: 4 February 2020)

scripts for specifying the considered DLCs, so that for each of the 54 DLC simulations defined in Sect. 4.1 the respective environmental conditions (as presented in Table 3) are assigned to the corresponding model variables. Similar modifications of values of system variables are made within the iterative optimization algorithm, as explained in Sect. 4.3.3. In the second step, the model simulations are managed, as both parallel and successive execution is possible, depending on the user's preferences and the available processors. The main step is then the execution of the simulations, as well as additional post-processing scripts and documentation tasks. At this point also any iterative optimization algorithm, defined through the optimization problem, the optimizer, and the final optimization algorithm, (covered in Sect. 4.3) takes effect. Finally, the simulation results and any further specified results file are the output from the programming framework.

More detailed information on the Python-Modelica framework, both regarding the theory and structure, as well as its capabilities and some application examples, can be found in the publications by Leimeister et al. (2020b) and Leimeister et al. (2019).

### 4.3 Specification and execution of the iterative optimization approach

As displayed in Fig. 2, the iterative optimization algorithm (Sect. 4.3.3) coupled to the Python-Modelica framework requires in addition to the model and simulation information also the definition of the optimization problem (Sect. 4.3.1) and specification of the optimizer (Sect. 4.3.2).

#### 4.3.1 Optimization problem

The optimization problem comprises the specification of design variables, objective functions, as well as constraints. This is defined and described in detail in Sect. 3 and, hence, consists of seven design variables (diameters and heights of each of the three BC parts, as well as height of the ballast), one objective function for the structure material volume of the advanced spar-type floater, and 25 inequality constraints (14 for the allowable value ranges of each of the design variables, three for the floating system performance, two for the draft requirements, and six for compliance checks regarding the filling capacity and actual ballast height, feasible ballast densities, as well as the cylinder diameters and wall thicknesses). These are directly implemented in the Python-Modelica framework, based on the definitions given in Sect. 3.

#### 4.3.2 Optimizer

From the broad range of available algorithms and methods (Leimeister et al., 2020b), only gradient-free optimization algorithms can be chosen for the application to complex fully-coupled wind energy systems modeled by means of the MoWiT library. From the implemented and tested optimizers NSGAI (Non-dominated Sorting Genetic Algorithm II), NSGAIII (Non-dominated Sorting Genetic Algorithm III), and SPEA2 (Strength Pareto Evolutionary Algorithm 2) - all from Platypus<sup>16</sup> - NSGAI is found to be the most suitable optimizer for the multi-objective optimization problem in the first-stage design optimization application example on a common floating offshore spar-buoy wind turbine system (Leimeister et al., 2020c). As a genetic

<sup>16</sup><https://platypus.readthedocs.io/en/latest/> (Accessed: 6 April 2020)

algorithm can deal with both formulations of an optimization problem (single-objective and multi-objective) and, hence, also with the optimization problem considered in this study, which holds only one objective function as defined in Sect. 3.2, and as the system simulations with the iterative optimization algorithm based on NSGAI can be also parallelized in a highly efficient manner, it is stuck in this work to the well-performing - both with respect to the convergence speed and the compliance rate concerning the constraints - optimizer NSGAI.

For the genetic algorithm NSGAI, which follows the principle of Darwin’s theory of evolution - meaning having individuals which develop further and further each generation towards performing better with respect to the fitness (objective) function -, the number of individuals in each generation (the population size) and the stop criterion for terminating the iterative optimization algorithm have to be defined.

- Due to the complex optimization problem with seven design variables and 25 constraints, the population size is set equal to the maximum possible number of processors, on which simulations can be run simultaneously. On an AMD Ryzen Threadripper 2990WX 32-Core Processor with 64-bit system and 64 virtual processors 60 processors could be used for parallel simulations. Hence, 60 individuals are considered in each generation.
- The stop criterion for terminating the iterative optimization algorithm is defined through the total number of simulations to be performed, while the convergence is checked separately when post-processing the simulation results. As the convergence speed is not known ahead of the execution of the specific optimization problem, the experience from the first-stage design optimization application example (Leimeister et al., 2020c) is used and the total number of simulations is increased to account for the much more complex optimization problem considered in this study. Hence, the resulting number of generations being simulated is roughly tripled, so that a total number of simulations of 10,000 is chosen, corresponding to more than 166 full generations with 60 individuals each.

### 4.3.3 Optimization algorithm

Now, having defined and modeled the floating offshore wind energy system as described in Sects. 2.2 and 2.3, stating the simulation settings as given in Table 5, having specified the optimization problem (see Sects. 3 and 4.3.1), and having selected the optimizer and corresponding parameter values as outlined in Sect. 4.3.2, the iterative optimization algorithm can be executed by means of the Python-Modelica framework for automated simulation and optimization.

**Table 5.** Simulation settings.

Simulation variable	Value	Note
simulation interval	from 0 s to 800 s	the first 200 s are accounted for as pre-simulation time to exclude any transients
output interval length	0.05 s	
solver	Rkfix4	(Runge-Kutta fixed-step and 4th order method)
fixed integrator step-size	0.01 s	

Within the iterative optimization algorithm, the values of the design variables for the 60 individuals of the first generation (number 0) are selected by the optimizer based on the specified allowable value ranges. All individuals are simulated in parallel on the available 60 processors and analyzed afterwards by the optimizer with respect to their fitness - meaning the objective function - and their compliance with the constraints based on the resulting time series, evaluated between 200 s and 800 s. As  
 475 also simulations may have failed (due to too bad performance or instability of the considered floating wind turbine system), the simulated time is checked against the specified simulation stop time (800 s according to Table 5). In case of an unsuccessful simulation and hence incomplete time series, the parameters of interest addressed in the constraints  $g_{15}$  to  $g_{17}$  for the system performance are not taken by evaluating the time series but are set equal to twice the maximum allowable value, meaning

$$\begin{aligned}
 & - \max(\text{total inclination angle})|_{\text{failing system}} = 2 \cdot 10.0^\circ = 20.0^\circ \\
 480 \quad & \Rightarrow g_{15}(\text{system}(X)|_{\text{failed}}) = 20.0^\circ - 10.0^\circ = 10.0^\circ \not\leq 0 \\
 & - \max(\text{horizontal nacelle acceleration})|_{\text{failing system}} = 2 \cdot 1.962 \text{ m/s}^2 = 3.924 \text{ m/s}^2 \\
 & \Rightarrow g_{16}(\text{system}(X)|_{\text{failed}}) = 3.924 \text{ m/s}^2 - 1.962 \text{ m/s}^2 = 1.962 \text{ m/s}^2 \not\leq 0 \\
 & - \text{mean translational motion}|_{\text{failing system}} = 2 \cdot 64.0 \text{ m} = 128 \text{ m} \\
 & \Rightarrow g_{17}(\text{system}(X)|_{\text{failed}}) = 128 \text{ m} - 64.0 \text{ m} = 64.0 \text{ m} \not\leq 0
 \end{aligned}$$

485 This way, it can be ensured that unsuccessful simulations do not comply with all constraints and, hence, are undesirable design solutions, which the optimizer then discards from further selection of well-performing individuals.

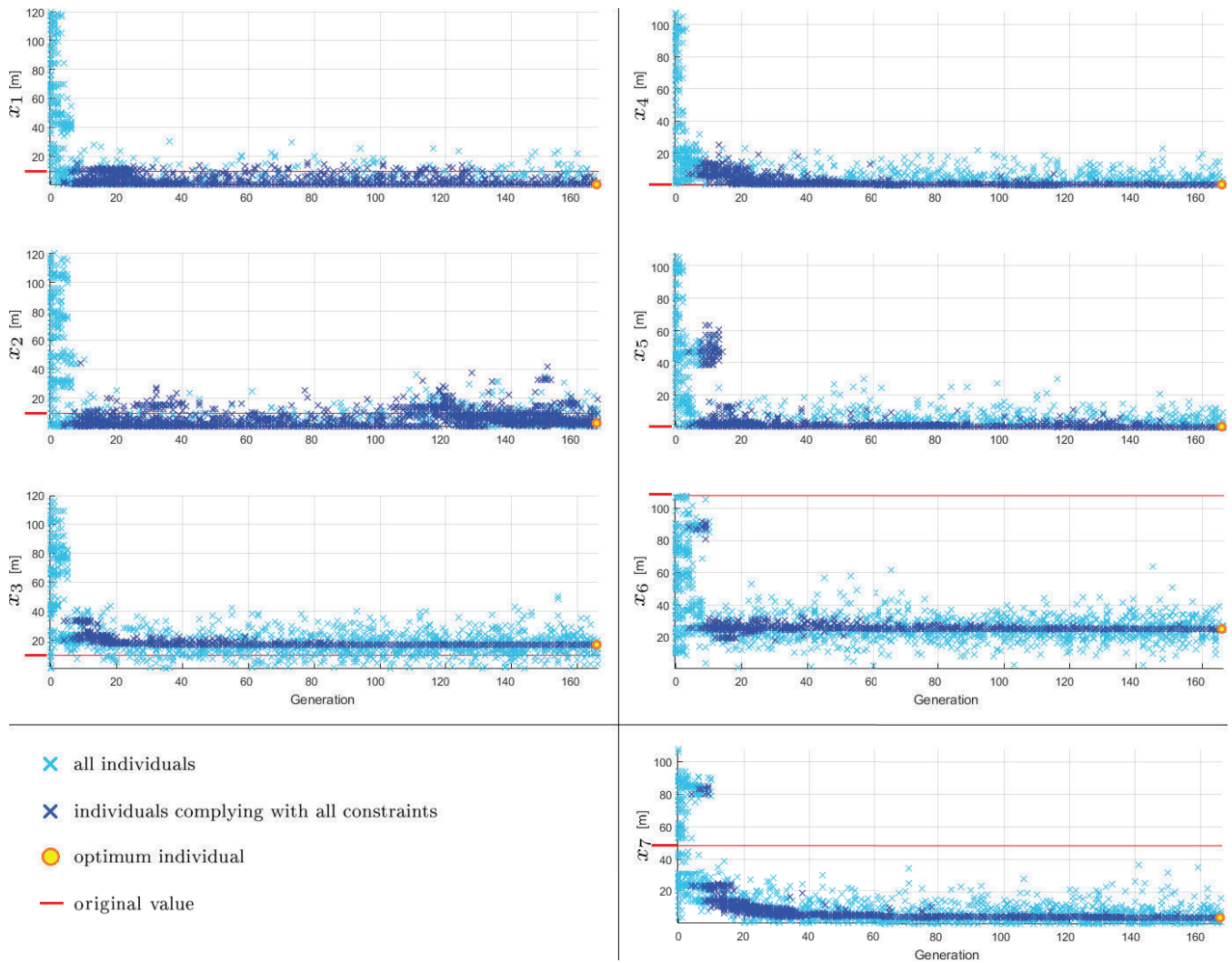
Having evaluated the simulated individuals of generation 0, the optimizer selects the design variables for the individuals of the next generation (number 1), again in accordance with the specified allowable value ranges, but also based on the fitness and constraints compliance rate of each of the previous individuals. Then, the loop of simulating the individuals, evaluating  
 490 each system with respect to the objective function and constraints, and re-selecting values (from the allowable value ranges) for the design variables of the individuals of the next generation based on the performance of the individuals in the previous generation is repeated as long as the number of executed simulations is still below the specified total number of simulations of 10,000. This iterative optimization algorithm ends when the stop criterion is reached - the final results are now available.

## 5 Results

495 The optimization algorithm with the specified optimization settings is executed; however, the simulation run has to be interrupted due to a required system restart. At that time already 8,133 individuals have been simulated. To complete the specified 10,000 simulations without having any disruptive effects on the final results, the optimization is continued by providing the individuals of the last wholly simulated generation 133 as start population of the subsequent optimization execution, utilizing the operator InjectedPopulation available in Platypus. Thus, the optimization run takes effectively about 31 days and eleven hours  
 500 and comprises 10,011 individuals simulated in total, ranging from generation 0 up to generation 166, with full populations up to and including generation 165.

### 5.1 Developments throughout the iterative optimization process

Figure 3 shows in light blue for all simulated individuals of the optimization run the values for the design variables  $x_1$  to  $x_7$ , as defined in Sect. 3.1. The values of the design variables of the reference advanced spar-type floating wind turbine system, covered in Sect. 2.3, are plotted additionally as red lines for comparative purposes. Post-processing of the simulation results and checking the constraints yield the dark blue recolored individuals which comply with all specified constraints. The finally selected optimum, which is presented in Sect. 5.3, is marked with a yellow filled circle framed in orange.



**Figure 3.** Development of the design variables throughout the iterative optimization process.

The developments of the design variables throughout the iterative optimization process show that in the first generations, the optimizer selects individuals covering the entire design space; however, none of the first is meeting all requirements. With more

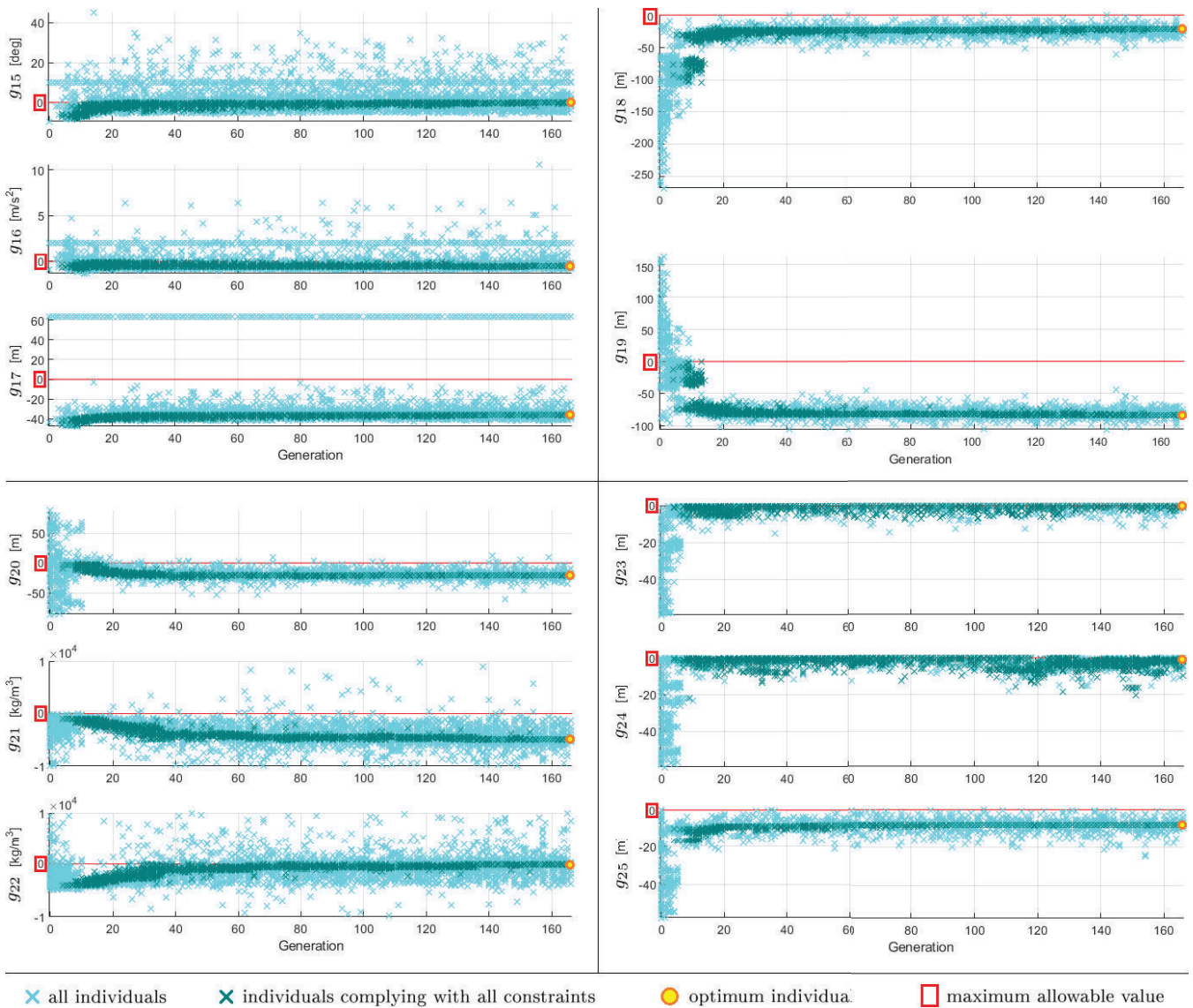
510 generations, the compliance rate is significantly increased, while it slightly decreases again when the focus of minimizing the objective function is coming more to the fore again. Overall, the spread in the design variables is decreased for more generations being simulated and for some design variables the change in their values is even very limited for the individuals which comply with all constraints. This indicates that the optimization algorithm is converging, though it has not yet fully converged, which is underlined by the fact that the optimum originates from the last generation.

515 Similarly, the developments of the constraints  $g_{15}$  to  $g_{25}$  throughout the iterative optimization process are analyzed and presented in Fig. 4. The first 14 constraints for the allowable value ranges of the design variables are excluded, as they are not constraints that are evaluated after the simulation, but are taken into account ahead of the simulations when the optimizer selects the design variables for the new individuals and, hence, are never violated. This can clearly be seen in Fig. 3, where all individuals lie within the allowable value ranges of the design variables. In Fig. 4, the light cyan crosses indicate the results for  
520 all simulated individuals, while the individuals which simultaneously comply with all constraints are recolored in dark bluish green. The limits of the inequality constraints, which should all be less or equal to zero, are indicated in red and the finally selected optimum is marked again with a yellow filled circle framed in orange. For  $g_{21}$  and  $g_{22}$  it has to be noted that the ordinate is limited to  $[-1E+4, 1E+4]$  for reasons of clarity, as a few more individuals yield values in the order of magnitude of six.

525 For  $g_{18}$  to  $g_{20}$  and  $g_{23}$  to  $g_{25}$ , which are directly related to and dependent on the design variables, the developments of the constraints show a similar behavior as the developments of the corresponding design variables throughout the iterative optimization process. For the other constraints, the trend is rather different, having a large spread in the results throughout the simulated generations. The fact that for  $g_{15}$  to  $g_{17}$  only a few distinguishable individuals are plotted in the first generations is caused by the large number of unsuccessful simulations in the first trials of the optimizer, for which reason the performance  
530 variables are set to the undesired values, as explained in Sect. 4.3.3, and, hence, are all the same for all failing systems. This is as well visible throughout the generations, as there is a line at the specified undesired value formed by the individuals that do not complete the simulations successfully.

## 5.2 Advanced spar-type floater geometries in the design space

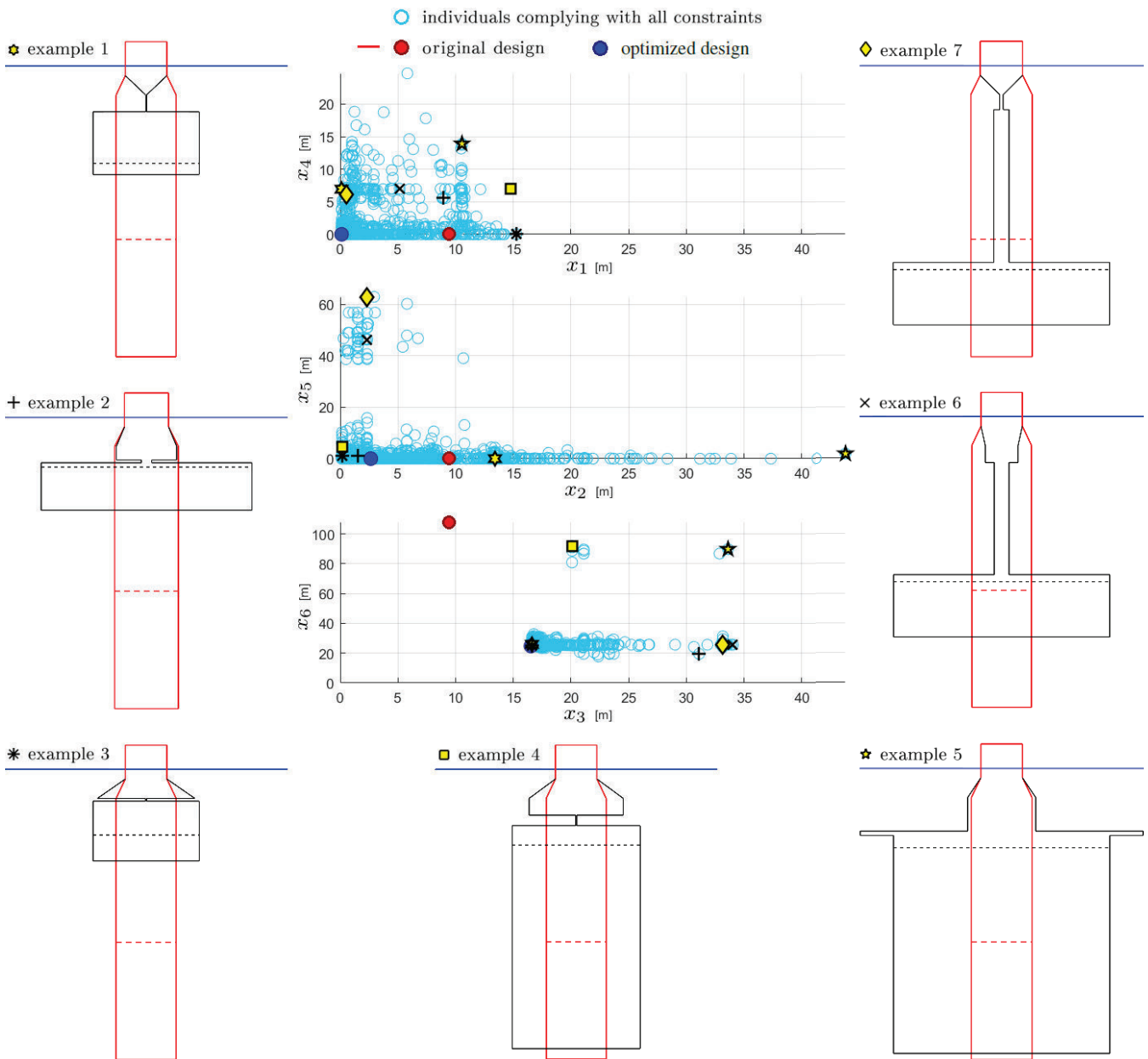
As presented and mentioned in Sect. 5.1, the individuals of the first generations cover the entire design space, specified through  
535 the set allowable value ranges as prescribed by means of the constraints  $g_1$  to  $g_{14}$ . The individuals that comply with all constraints, however, are in a much more narrow area of the design space. The geometric design variables  $x_1$  to  $x_6$  of these individuals, setting height and diameter of each BC part in correlation, are plotted in light blue unfilled circles in Fig. 5. The original and optimum designs are highlighted by red and blue, respectively, filled circles. From these individuals, which comply with all constraints, seven examples are selected to demonstrate the diversity of potential (meaning successful but maybe  
540 not yet optimum) advanced spar-type floater geometries. These examples are schematically drawn with black lines in Fig. 5 together with the original shape in red and having represented the ballast heights in dashed lines. The corresponding figures for design variables, performance parameters, objective function, and further resulting geometrical and structural parameters



**Figure 4.** Development of the constraints throughout the iterative optimization process.

of the presented examples are outlined in Table 6. These numbers also underline that - when evaluating  $g_1$  to  $g_{25}$  - none of the inequality constraints is violated.

545 Looking at the floater geometries presented in Fig. 5, it becomes clear that not all of these shapes can be realized with conventional structural solutions, where cylindrical sections are welded together. It has to be emphasized that these results are solely based on the hydrodynamic and system-level analyses, as specified within the optimization problem. Other additional types of analyses - addressing structural integrity, manufacturability, and localized design - can, hence, deem some of the presented potential design solutions unfeasible, which is discussed in some more detail in Sect. 6. However, the advantage



**Figure 5.** Exemplary potential advanced spar-type floater geometries selected from the individuals complying with all constraints.

550 of this methodology - by focusing only on the hydrodynamics - is that a new range of potential floater designs is opened up and shapes like these presented in Fig. 5 can still be considered as feasible solutions when different structural realization approaches are applied. These approaches can range from truss structures to tendons to realize large diameter changes, as well as very thin elements, without utilizing tapered sections or having issues with the structural integrity. Idea and impulse provider



**Table 6.** Key figures of the exemplary potential advanced spar-type floater geometries.

Ex.	Gen.	Ind.	$x_1$ [m]	$x_2$ [m]	$x_3$ [m]	$x_4$ [m]	$x_5$ [m]	$x_6$ [m]	$x_7$ [m]	Ballast density [kg/m <sup>3</sup> ]	Wall thickness [m]	Draft [m]
1	115	45	0.116	13.410	16.612	6.930	0.002	25.903	4.573	4.585E+03	0.0578	44.836
2	14	15	8.899	1.528	31.100	5.551	1.183	19.518	17.774	1.003E+03	0.1052	38.252
3	78	32	15.253	0.164	16.612	0.018	1.109	25.033	10.709	2.156E+03	0.0580	38.160
4	8	6	14.755	0.172	20.090	6.970	4.665	91.993	84.016	1.037E+03	0.0797	115.628
5	9	45	10.550	43.919	33.605	13.896	1.798	89.776	84.684	1.008E+03	0.1344	117.470
6	10	8	5.158	2.331	34.015	6.997	46.270	25.683	22.727	1.022E+03	0.1135	90.950
7	9	57	0.523	2.331	33.154	6.159	62.944	25.683	22.727	1.013E+03	0.1106	106.786

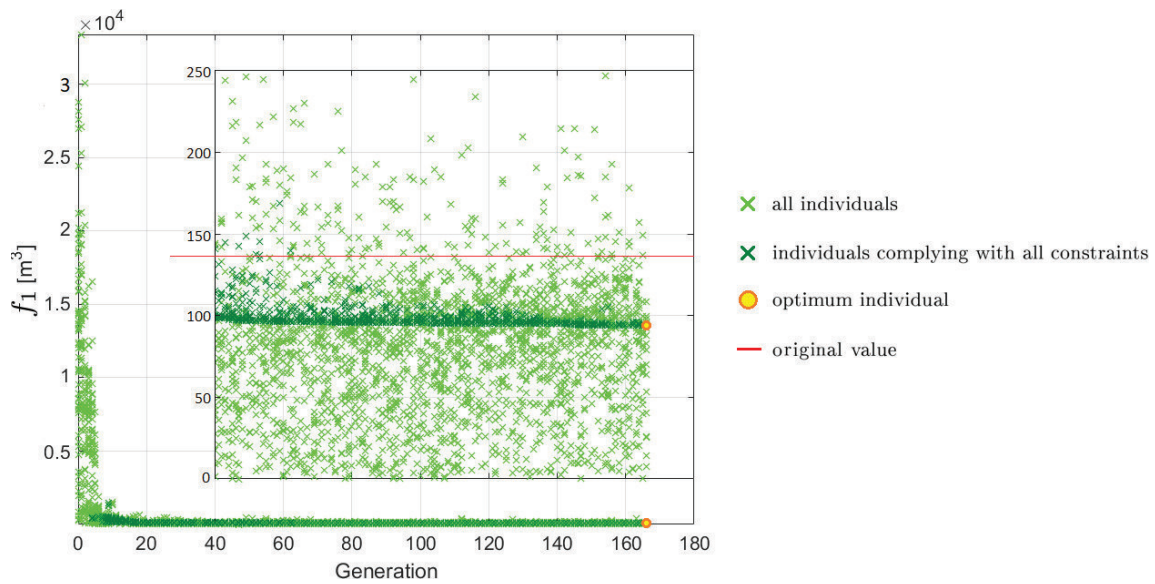
Ex.	Max(tot. inclination angle) [°]	Max(hor. nacelle acceleration) [m/s <sup>2</sup> ]	Mean(transl. motion) [m]	$f_1$ [m <sup>3</sup> ]	Steel mass [kg]	Ballast mass [kg]
1	9.9	1.337	28.155	99.1	7.778E+05	4.544E+06
2	5.0	1.231	22.241	266.2	2.090E+06	1.355E+07
3	9.3	1.724	27.308	107.7	8.455E+05	5.004E+06
4	2.6	1.955	17.503	530.1	4.162E+06	2.761E+07
5	1.6	1.664	21.089	1428.6	1.121E+07	7.570E+07
6	3.9	1.447	21.109	407.9	3.202E+06	2.111E+07
7	4.6	1.159	22.138	384.8	3.021E+06	1.987E+07

for such different structural realization approaches can be for example **the oil and gas industry** (Chen et al., 2017; Perry et al., 2007; Bangs et al., 2002) **or** innovative floating platform concepts, such as the TetraSpar by Stiesdal A/S (Stiesdal, 2019) or the pendulum-stabilized Hexafloat floater by Saipem, realized in the AFLOWT project (Richard, 2019).

### 5.3 The optimized advanced spar-type floater

Due to the single-objective nature of the optimization problem, the selection of the optimum solution happens directly through evaluating the one and only objective function. This means that from all individuals that comply with all constraints, this is chosen as optimum which exhibits the lowest value for the structure material volume of its advanced spar-type floating platform design.

First, looking at the development of the objective function  $f_1$  throughout the iterative optimization process, as presented in Fig. 6, the trend of all simulated individuals (plotted in light green) shows a significant minimization of the objective function - clearly below the original value of 136.3 m<sup>3</sup>, indicated in Fig. 6 by a red line - after a large spread in the first generations.



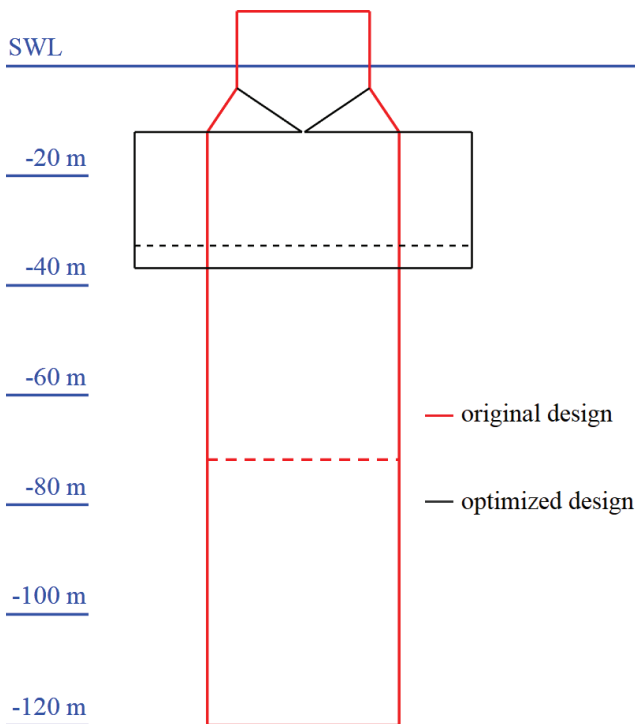
**Figure 6.** Development of the objective function throughout the iterative optimization process.

565 Zooming into the objective function results from generation 40 on, as included in Fig. 6, provides a much clearer indication of the development of the minimum structure material volume for the individuals which comply with all constraints (recolored in dark green): they aggregate to an asymptote. This is already visible in early generations; however, the spread in the objective function results of the individuals complying with all constraints is decreasing with more generations being simulated. This asymptotic clustering of the individuals which comply with all constraints to a minimum objective function value on the one  
 570 hand states the convergence of the iterative optimization process and on the other hand portends that there will be several - more or less similar (elaborated in the following) - design solutions, which yield comparable low structure material volumes that are all very close to the minimum value observed.

The individual with the minimum structure material volume is pointed out in Fig. 6 by means of a yellow filled circle framed in orange. This design solution yields a reduction of the structure material volume of more than 31% compared to the  
 575 original (modified) advanced spar-type floating platform. The fact that this optimum solution is just found in the last generation simulated states that full convergence is not yet reached, despite the converging trend in most of the design variables and constraints, as well as in the objective function. Nevertheless, due to the asymptotic aggregation of the individuals mentioned above, the first ten minimum objective function results from the individuals which comply with all constraints are evaluated. This results - as some individuals yield the same objective function value - into 16 individuals with a just by 2.84E-4% increased  
 580 structure material volume, comparing the tenth lowest with the minimum value, and shapes that are difficult to distinguish from each other. This proves the above mentioned anticipation that - due to the convergence of the iterative optimization process and the aggregation of the individuals' objective function results to an asymptote - several very similar advanced spar-type floater design solutions of comparable low structure material volumes are found.

The geometry of the optimized advanced spar-type floater shape (black line) is shown schematically in Fig. 7 in comparison to the original floating platform drawn in red. The key figures of the optimized advanced spar-type floater geometry are presented in Table 7. The found design solution is - as already mentioned - out of the last generation, indicating that the optimizer is still searching for individuals with lower structure material volume; however, the improvement within the last simulated generations is negligible as outlined above. Both Fig. 7 and Table 7 indicate the following design development trend within the iterative optimization process: to reduce the structure material volume

- the overall length of the floating platform is significantly decreased compared to the original geometry - the draft of the advanced spar-type floater is, however, still significantly away from the minimum allowable draft of 15 m;
- the width of the bottom part of the support structure is enlarged, while
- the upper and middle parts are almost left out, leading to this significant constriction in the tapered part; and
- a very low ballast volume is obtained through a significantly increased ballast density, utilizing MagnaDense or high density concrete as ballast material.



**Figure 7.** The optimized advanced spar-type floater geometry in comparison with the original shape.

**Table 7.** Key figures of the optimized advanced spar-type floater.

Key figure	Value
Generation	166
Individual	51
$x_1$	0.115 m
$x_2$	2.653 m
$x_3$	16.525 m
$x_4$	0.001 m
$x_5$	3.0E-8 m
$x_6$	24.761 m
$x_7$	4.098 m
Ballast density	4.855E+03 kg/m <sup>3</sup>
Wall thickness	0.0571 m
Draft	36.762 m
Max(tot. inclination angle)	10.000°
Max(hor. nacelle acceleration)	1.426 m/s <sup>2</sup>
Mean(transl. motion)	28.394 m
$f_1$	93.9 m <sup>3</sup>
Steel mass	7.373E+05 kg
Ballast mass	4.267E+06 kg

The system performance - maximum total inclination angle, maximum horizontal nacelle acceleration, and mean translational motion - points out that the maximum total inclination angle is the most critical performance criterion, as the obtained value from the optimized design is equal to the specified upper limit of  $10^\circ$ .

Overall, the shape of the optimized advanced spar-type floater design resembles rather a submerged thick barge-type floater, hanging below the upper column element. This constriction in the tapered part is significant and would not directly be technically feasible, both from a manufacturing point of view and with respect to structural integrity. The reason for the current shape obtained is the connection of the upper column to the upper BC part, which, however, is, as well as the middle BC part, negligible. Thus, the tapered part could directly connect the end of the upper column with the top of the lower BC part, which is mainly purely the base column of the advanced spar-type floater. The change in required structure material would be not that significant; however, the related change in the displaced water volume has to be taken into account by adjusting the structure mass and by carefully evaluating the system performance due to the shifted center of buoyancy. This realization by means of a tapered section, however, comes with a large diameter change and corresponding large taper angle, which may be critical for both hydrodynamic load calculations and manufacturing, as discussed in more detail in Sect. 6. However, the structural issues due to the geometrical configuration of the optimized floater as presented in Fig. 7, or as well as due to the large diameter change when utilizing a tapered section, become void when eliminating the negligible upper and middle BC parts and connecting the upper column and lower BC part by means of a number of rigid slender braces or some tendons, **in combination with plated partial bulkheads for load transfer**, instead of **using** a tapered segment. These manufacturing solutions go beyond the conventional structural realization approach of welding cylindrical sections together, but they make the found optimized floater design solution feasible and are expected to represent similar system performance. The fitness of the floater solution proposed by the optimizer is underlined due to its similarity **(with respect to the innovative structural realization approach)** to the most novel and alternative solutions suggested by the research community, such as the Stiesdal's TetraSpar (Stiesdal, 2019) or the Hexafloat by Saipem (Richard, 2019).

#### 5.4 Performance of the optimized system in different environmental conditions

With the design solution for the advanced spar-type floating offshore wind turbine platform obtained from the optimization run, finally, the DLCs that are selected for the preprocessing automated system simulations for choosing the most critical DLC (as presented in Sect. 4.1) are rerun to check whether a shift in the most critical DLC happens. The criticality is again assessed by evaluating the fully-coupled system performance criteria (maximum total inclination angle, maximum horizontal nacelle acceleration, and mean translational motion) and analyzing the corresponding constraints  $g_{15}$  to  $g_{17}$ . The highest values and corresponding DLC simulation cases, as well as the values obtained with the selected DLC 1.6 at rated wind speed with wind seed number 11 and yaw misalignment angle of  $8^\circ$ , are presented in Table 8.

For the design solution from the optimization run, there is a shift in the criticality of the DLCs observed. The smallest change in the order of criticality of the 54 environmental conditions happens in the horizontal nacelle acceleration. Still the cases from DLC 1.6 at cut-out wind speed, as well as around rated wind speed, are most critical, but the DLC used within the iterative optimization algorithm is still among the first ten with an acceleration value that is almost 12% lower compared to the maximum

**Table 8.** The highest values for the three performance parameters and corresponding DLC simulation cases, based on the optimized advanced spar-type floating system.

Position	DLC	Wind speed	Wind seed	Yaw misalignment	Max(total inclination angle)
1	1.1	13.0 m/s	18	8°	12.061°
2	1.1	11.4 m/s	10	0°	12.011°
3	1.3	11.4 m/s	10	0°	12.011°
4	1.1	11.4 m/s	7	-8°	11.903°
5	1.3	11.4 m/s	7	-8°	11.903°
30	1.6	11.4 m/s	11	8°	10.000°

Position	DLC	Wind speed	Wind seed	Yaw misalignment	Max(horizontal nacelle acceleration)
1	1.6	25.0 m/s	17	8°	1.620 m/s <sup>2</sup>
2	1.6	25.0 m/s	18	8°	1.618 m/s <sup>2</sup>
3	1.6	25.0 m/s	13	-8°	1.550 m/s <sup>2</sup>
4	1.6	25.0 m/s	16	0°	1.521 m/s <sup>2</sup>
5	1.6	25.0 m/s	15	0°	1.480 m/s <sup>2</sup>
10	1.6	11.4 m/s	11	8°	1.426 m/s <sup>2</sup>

Position	DLC	Wind speed	Wind seed	Yaw misalignment	Mean(translational motion)
1	1.1	13.0 m/s	15	0°	31.564 m
2	1.1	11.4 m/s	9	0°	31.375 m
3	1.3	11.4 m/s	9	0°	31.375 m
4	1.1	13.0 m/s	17	8°	30.631 m
5	1.1	11.4 m/s	12	8°	30.337 m
22	1.6	11.4 m/s	11	8°	28.394 m

630 obtained from all simulated DLCs. This, however, is itself still more than 17% below the maximum allowable horizontal nacelle  
acceleration and, hence, uncritical, which - on a side note - is not the case for the original floating spar-buoy wind turbine  
system. A significant increase in the resulting performance values and considerable change in the order of criticality of the  
environmental conditions is obtained for the mean translational motion. Here, the selected DLC for the optimization process  
drops down from the originally sixth position to the 22nd, while it is just 10% below the highest value achieved, which is still  
635 less than half of the maximum allowable value and, hence, again uncritical. However, the most sever shift in the criticality of the  
DLCs happens for the total inclination angle of the system. As indicated in Sect. 5.3, the maximum allowable value is already  
reached in the environmental condition considered for the optimization approach. This DLC, however, is for the obtained

optimized design solution no longer prevailing but just on the 30th position, meaning that 29 other environmental conditions (mostly from DLC 1.1 and DLC 1.3, as well as some others from DLC 1.6) exceed the specified upper limit by up to more than 640 20%. In these environmental conditions, the floater designs obtained from the optimization run would have to stop operation, while the overall system stability is not expected to be critical, as commonly much higher values for a parked floating wind turbine system in extreme environmental conditions are acceptable, such as 15° considered by Hegseth et al. (2020). However, to avoid reduced system availability, the occurring changed criticality of the DLCs has to be addressed already during the optimization - by for example considering safety factors for such critical and design-driving performance criteria - and the 645 performance in all environmental conditions can be further improved by subsequent optimization of the currently unaltered mooring system. These options are discussed in more detail in Sect. 6.

## 6 Discussion

In addition to the presented, analyzed, and discussed results in Sect. 5, these are addressed in more detail and further aspects are discussed in the following.

650 Based on the results and findings from the DLC simulations with the optimized advanced spar-type floating wind turbine system design, it is recommended to take some safety factors for the maximum allowable performance values into account. If the horizontal nacelle acceleration would have been exceeded in some of the 54 environmental conditions, it would not have been that critical, as a maximum allowable value of up to 0.3 times the gravitational acceleration constant - and not only 0.2 times as applied - is often accepted, as already mentioned in Sect. 2.4. The specific maximum allowable values for an operating 655 floating offshore wind turbine system have to be provided by the turbine manufacturer or operator. Thus, maybe a higher inclination angle is still acceptable; however, if 10° are really the uppermost tolerated angle, a value of 8° or maximum 9° shall be used for the optimization constraint. A reduced maximum allowable total inclination angle can as well afterwards be applied in the post-processing of the results and this way an in all 54 environmental conditions well-performing floater design can be obtained, with the downside that a larger structure material volume is required and that this design does not represent an 660 optimized solution. A profitable option, hence, is to adjust the - currently excluded and unchanged - mooring system properties and layout design. By modifying these in a subsequent optimization task, the optimized floater design can be retained and at the same time the performance of the floating offshore wind turbine system in all considered environmental conditions improved - in this case especially the system inclination. **Apart from the considered 54 environmental conditions, however, the optimized floating offshore wind turbine system design has to prove to withstand any potential environmental and operational condition during its design life. Thus, for a subsequent more realistic analysis, the entire set of DLCs recommended by standards,**

- **considering more realistic environmental conditions by accounting for various natural periods per considered sea state,**
- **capturing the low frequency dynamics of the floating wind turbine system through utilization of longer simulation times,**  
**and**

670 – including also load cases with occurrence of a fault - such as grid loss - or with other transient loads - due to, for example, gusts - which might cause high accelerations and extreme loads, has to be considered - at least in the pre-selection and final reassessment of the selected critical load case.

Considering the wide design space - especially the broad allowable value ranges for the structural diameters - and the extreme environmental conditions, included in the DLC simulations, some refinements in the model with respect to the hydrodynamic calculations are suggested.

675 – For an accurate representation of the hydrodynamic loads on the floating structure, the hydrodynamic coefficients have to be recalculated for each specific diameter. While the horizontal added mass coefficient, as well as the total inertia force, are already determined in dependency of the actual structural diameter and wave number, as the MacCamy-Fuchs approach is applied for each column element separately, the horizontal drag coefficient is currently not altered from the original value of 0.6. This is a valid assumption for large diameters already at low flow velocities; however, 680 for small diameter structures, which can occur within the optimization algorithm, an around twice as large horizontal drag coefficient might be applicable (Clauss et al., 1992). In the vertical (heave) direction, both added mass and drag coefficients are currently unchanged, while a vertical Froude-Krylov excitation force is considered, accounting for the difference between UC diameter and the diameter at the floater base. Especially for geometries with large diameter changes, as well as with large diameters, which can be regarded as heave plates, the hydrodynamic coefficients will 685 differ from the original values for a continuous cylinder as the OC3 phase IV spar-buoy. Furthermore, the vertical Froude-Krylov excitation force would have to be adjusted to the specific geometry, when the lower BC part is connected by means of trusses or tendons to the upper column, to account for the differences between each upper and lower surfaces. This both - changes in the hydrodynamic coefficients in heave direction and adjusted vertical Froude-Krylov excitation force - will mainly affect the heave motion of the floating system, as well as the roll and pitch motions in some respect. 690 With the geometry obtained from the optimization, however, it is expected to experience less strong system responses if the hydrodynamic coefficients are adjusted accordingly - which would benefit for example the system inclination - while the system responses will increase slightly if the vertical Froude-Krylov excitation force is determined accurately for the considered geometry.

695 – For more extreme environmental conditions with extreme waves and similar structures as obtained with the optimization run, which tend to have a large diameter directly at or close to the top of the BC, the event that the upper surface of such a large diameter cylinder becomes dry has to be accounted for when calculating the added mass and damping coefficients in order to not overestimate the heave and pitch added mass and, thus, to not underestimate the horizontal nacelle acceleration in case of more energetic sea states. Furthermore, having a horizontal surface close to the water surface - in the presented settings with a minimum distance of 12 m - could be as well critical structurally or maybe 700 due to the impossibility of common service vessels to approach the wind turbine. However, it has to be noted that it is aimed to establish a floating platform optimized with respect to the hydrodynamics. This, then, needs to be compromised

imposing other prevailing constraints, such as structural limits - as discussed later in more detail again - or accessibility, for which for example walk-to-work solutions with a gangway can be exploited.

705 – The applied MacCamy-Fuchs approach is in principle just valid for cylinders with vertical walls and not for cylinders with abrupt changes of diameters, leading to conical sections or even large horizontal surfaces anywhere along the column (the latter one, however, is considered again by means of the vertical Froude-Krylov excitation force, as discussed previously). If the MacCamy-Fuchs approach is applied to conical structures, the wave load from especially waves with low periods will be underestimated. This could be in the order of magnitude of up to 8% or 14% for a cone angle of around  $6.7^\circ$  or  $12.2^\circ$ , respectively, and could affect wave periods of 3 s to 6 s or 3.5 s to 7 s, according to investigations on a tapered bottom-fixed offshore wind turbine support structure (Leimeister, 2019). Thus, this potential underestimation of the hydrodynamic loading is mostly relevant for the environmental conditions of DLC 1.1, as well as for the below and at rated wind speed cases of DLC 1.3. For the design solution proposed in Sect. 5.3, in which the bottom end of the upper column is directly connected with the large diameter lower BC part, the taper angle would amount  $32^\circ$ . Any hydrodynamic calculations based on the MacCamy-Fuchs approach would no longer be meaningful if the design solution is realized by means of a solid tapered part. Thus, the alternative suggestion of having instead a number of rigid slender braces would be favored. In order to ensure valid computation of the hydrodynamics already within the optimization approach, another constraint on the maximum taper angle shall be added, as implemented with a limit of  $10^\circ$  by Hegseth et al. (2020). This aspect is, however, less critical when allowing for different structural solutions, where trusses or tendons prevent any utilization of strongly tapered sections.

720 As addressed and discussed in Sects. 5.2 and 5.3, the geometrical configuration of the potential and optimized advanced spar-type floaters as presented in Figs. 5 and 7 may not be technically feasible from a structural integrity and manufacturability point of view, adopting the standard manufacturing solutions. For obtaining a high detail structural design, further localized analyses and assessments regarding the manufacturability have to be performed subsequently. However, structural integrity checks for buckling or stress concentration and for accounting for a realistic and adjustable base and lid thickness, which is currently just set to a fixed marginal value, can as well directly be integrated in the definition of the optimization problem. Nonetheless, based on the assumptions and focus of this study, which is on hydrodynamic and system-level analyses, a significantly improved and more cost-efficient floater can be achieved. This is as well feasible when considering different structural realization approaches, such as braces and truss structures or tendons, as already used in the oil and gas industry (Chen et al., 2017; Perry et al., 2007; Bangs et al., 2002) or utilized in innovative floater concepts (Richard, 2019; Stiesdal, 2019), instead of following purely the conventional structural approach of welding cylindrical and tapered sections together.

730 Finally and admittedly, for really considering an optimization of the wind turbine system cost, the ratio of CapEx (Capital Expenditure) to AEP (Annual Energy Production) or even the LCoE, which additionally takes OpEx (Operational Expenditure) - and sometimes also costs of decommissioning - into account, would have to be considered to be minimized. This way, a real trade-off between saved material costs, changed expenditure of manufacturing and maintaining the system, and different system performance, and, hence, affected AEP can be found. However, this requires a more holistic and complex approach,



considering annual environmental distributions at the location of interest, calculations for the full life-time of the system, as well as knowledge of possible manufacturing processes and related costs. The present work can be further expanded in the future to take into account these steps and aspects.

## 7 Conclusions

740 In this paper, an automated optimization approach is applied to a floating offshore wind turbine system in order to design an advanced spar-type floating platform, which is optimized with respect to the change in hydrodynamics and their impact on the main system performance, while structural, manufacturability, or other constraints are not considered. This approach, following a freer optimization formulation, is taken in order to be able to explore novel design spaces which can be better from an hydrodynamic point of view, but that may require novel structural solutions approaches, as actively investigated by the community (e.g. Stiesdal's TetraSpar and Saipem's Hexafloat). The application is based on the OC3 phase IV spar-buoy floating offshore wind turbine system. This, however, is modified by dividing the spar-buoy base column into three distinct partitions, so that sufficient buoyancy, as well as a deep center of gravity can be obtained. Furthermore, the wall thickness is adjusted based on a common ratio of the support structure's structural mass to the displaced mass of water. The optimization focuses on the minimization of the steel volume of the floater, which represents an approximation of the CapEx of the support platform. In addition, constraints regarding the outer dimensions (meaning the allowable value ranges of the design variables), the global fully-coupled system performance, the system draft, the ballast, and the geometric integrity are defined. Having selected, based on preprocessing automated system simulations, one DLC which is most critical for the constrained system performance criteria, the iterative optimization algorithm run is performed, utilizing the Python-Modelica framework for automated simulation and optimization, as well as using the genetic algorithm NSGAI as optimizer. The analysis of the optimization simulation results shows that the individuals which comply with all prescribed constraints aggregate as for their objective function values to an asymptote. The results from the optimization run emphasize the complexity of the optimization problem and indicate that - despite the large number of simulations and the asymptotic clustering to a minimum objective function - full convergence is not yet obtained. Nevertheless, the applied iterative optimization algorithm presented in this study yields an advanced spar-type floating support structure design, which

- 760 – has a by more than 31% reduced structure material volume compared to the original floating platform,
- meets all global performance criteria for the considered critical DLC,
- has an overall draft of 36.8 m,
- utilizes MagnaDense or high density concrete as ballast material, and
- resembles a submerged thick barge-type floater.

765 The operability is - taking the maximum allowable system performance values as strict obligation for operating ability - limited to 46.3% of the considered 54 environmental conditions. This, however, can be much more extended when modifying

subsequently the currently unchanged mooring system properties and layout. Based on the applied hydrodynamic and system-level analyses an optimized initial advanced spar-type floater design is obtained, which has to be further refined by incorporating structural checks into the optimization process, but can be realized by means of innovative structural approaches, which utilize  
770 trusses or tendons instead of solely welding cylindrical sections together.

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