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Review

A review and analysis of optimisation techniques applied to floating offshore wind platforms

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ABSTRACT

The deployment of offshore wind in the UK has seen a rapid increase in the past decade and will continue to increase with the securement of the recent Scotwind sites. Floating platforms will be utilised for 60% of these new sites, creating opportunities to try new platform typologies and further solidify the validity of existing concepts. Since there is no consensus on the platform typology, the cost will vary; however, it is predicted to be double the price of traditional fixed platforms. Finding the most optimal solution in terms of cost and performance is key to keeping cost low, allowing the technology to be more competitive. A technique which has been used in other industries is multi-objective optimisation, searching a large design space much more quickly than traditional methods. By carrying out a multi-objective approach, the optimal platform geometry can be identified over the Pareto Frontier, considering conflicting objectives such as cost and performance. The aim of this work is to review the existing literature on multi-objective optimisation of floating offshore wind (FOW) platforms, highlighting the gaps and shortfalls in the current literature. This review highlights the majority of work has been carried out for the 5 MW NREL turbine on a SPAR platform, utilising a genetic algorithm. Cost reduction has been noted as the main objective, however, the models found within the literature are simplistic, with a number of assumptions. The overall findings of this work highlight future work that could be improved: cost models, the inclusion of an energy production model linked to the platform motion, the requirement for analysis of larger turbines and the potential for a concept selection tool to reduce computational time.

1. Introduction

As we approach 2050 and the deadline for net zero draws nearer, it is clear that a key player in the decarbonisation of the grid is wind, having proven successful both onshore and offshore (Rhodri and Ros, 2015; UKGovernment, 2021; Carbon Trust, 2018). However, the number of available nearshore sites is reducing, pushing operators to explore further afield into deeper, further offshore sites with the scope for larger capacity deployments (Buljan, 2022). Traditional fixed platforms are no longer techno-economically feasible at these depths (Hannon et al., 2019; Eric Paya, 2020; Lefebvre and Collu, 2012; Carbon Trust, 2023; Tong, 1998), resulting in the requirement for floating solutions. However, new technologies come with inherent risks and generally higher costs (Rhodri and Ros, 2015; Maienza et al., 2020; Myhr et al., 2014; Catapult, 2017). This is particularly relevant given that the industry has not yet found an "optimum configuration" suitable for every situation. It is therefore predicted that there will be no such universal solution due to variation in site characteristics and lack of maturity in the floating offshore wind industry, the latter being one of the driving factors of increased cost (ABS, 2021; EU, 2014). It is for this reason that cost reduction is of the utmost importance, ensuring green secure electricity is still affordable to the user (ofgem, 2022). The CAPital EXpenditure (CAPEX) makes up around 75% (Maienza et al., 2020; Kausche et al., 2018) of the total cost, making it a key area for cost reduction. For floating wind the two highest costs that make up the CAPEX are the rotor-nacelle assembly and the floating support structure, each around 35% (Maienza et al., 2020). This research focuses on the floating support structure, due to its large contribution to the CAPEX (Catapult, 2022). At present, few studies have addressed the concept of an optimal support structure. Instead, the focus has been on determining an optimal rotor nacelle assembly design (Tanmay, 2018; Shires, 2013; Lovell and Doherty, 1994; Jureczko et al., 2005; Shourangiz-Haghighi et al., 2020; Barnes and Morozov, 2016; Medici, 2005; Wang et al., 2016; Fagan et al., 2018; Chen et al., 2017; Collecutt and Flay, 1996; Cencelli, 2006). Optimisation is a technique which has been highly utilised in the automotive and aerospace industry to find an optimal design (Muskulus and Schafhirt, 2014). This process

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covers a large design space in a much shorter time frame compared to traditional, iterative design methods, making it appealing for a less mature industry (Muskulus and Schafhirt, 2014). Given the similarities to the aerospace industry and the lack of experience, it is expected that optimisation will be a useful tool in determining the best floating offshore support structure for a given application (Uzunoglu et al., 2016). Due to the high complexity and dependency of floating offshore wind systems, it is expected that a multi-objective approach will be necessary. By applying a multi-objective approach and a number of design constraints, the best overall solution can be found by removing unfeasible options, even when there are conflicting objectives such as cost and performance (Pike-Burke, 2019; Venter, 2010). This paper aims to review the current literature, determining the shortfalls and the potential improvements to such optimisation approaches.

Following this introductory section, Section 2 details the approach adopted to find the analysed literature, and in Section 3, optimisation-related works will be reviewed looking at the considered design variables, constraints, objective functions, solvers, and numerical approaches implemented. Section 4 will provide a critical discussion, while Section 5 will conclude with a summary of the work's findings and detail the proposed future work.

2. Literature review methodology

In order to conduct an extensive, yet relevant, review a wide range of keywords were used in a range of different search engines; these keywords include optimisation, floating offshore wind, and floating platform. This allowed a large number of papers to be collected. The most appropriate research from these papers were found by applying a number of criteria. The first criterion was to ensure the paper included the platform in the optimisation process, and this was not only restricted to floating offshore wind research, optimisation for Oil and Gas support structures were also considered. The second filter was based on the publication format of the research, i.e. firstly, if it was published in a conference proceeding, and if so, what was the highest h-index of the authors. If the index was above a set value the paper was used in the review. If the research was published in a scientific journal, the impact factor was reviewed, and if it was above the acceptable threshold, it was included. In the event that the journal impact or h-index was low, the author used their judgement to determine whether the article would be appropriate or not. Finally, if the research was published elsewhere the relevance and usefulness of the work was assessed by the authors. The explained methodology can be seen in Fig. 1.

The year of publication of each paper is reported in Fig. 2, this figure highlights that in recent years the topic has been increasingly growing in popularity within the industry.

3. Optimisation review

The outline of the subsequent Sections is as follows: Section 3.1 firstly details the generic multi-objective optimisation problem. The remaining Sections detail a review of the overall optimisation, objective functions, constraints, design variables and platform modelling, optimisation algorithms, modelling and additional software required, cost models used, and the overall outcome of each paper.

3.1. Optimisation problem methodology

The formulation, which details a general multi-objective design optimisation, can be expressed as

$$\min_{\boldsymbol{x}\in\mathbb{R}} \quad \boldsymbol{J}(\boldsymbol{x}) \tag{1}$$
$$\text{subject to} \quad \begin{cases} \boldsymbol{x}_{lower} \leq \boldsymbol{x} \leq \boldsymbol{x}_{upper} \\ h_i(\boldsymbol{x}) = 0; \quad i = 1, \dots, m \\ g_j(\boldsymbol{x}) \geq 0; \quad j = 1, \dots, p. \end{cases}$$

where $\boldsymbol{x} = [x_1, x_2, \dots, x_k]$ defines the design vector, which contains the design variables which are varied through the optimisation, and $\boldsymbol{J}(\boldsymbol{x}) = [J_1(\boldsymbol{x}), J_2(\boldsymbol{x}), \dots, J_n(\boldsymbol{x})]$ is an n-dimensional vector of objective functions. The design vector has upper and lower bounds, $\boldsymbol{x}_{lower}$ and $\boldsymbol{x}_{upper}$ respectively, which help to not only reduce the design space and computational time but consider more realistic design variables. In this notation, m and p are the numbers of equality and inequality constraints, respectively. In the situation where $\boldsymbol{J}(\boldsymbol{x})$ has competing components, there is no unique solution, and therefore the multi-objective solution will be found on the Pareto optimal set (Pike-Burke, 2019; Karimi et al., 2017). The frontier presents a set of optimal solutions, moving along the front to another optimal solution, will improve one objective but worsen another, all points on this frontier can be considered as solutions to the multi-objective optimisation problem (Pike-Burke, 2019; Karimi et al., 2017). This can then introduce preference from the user, selecting overall the best solution for their needs.

3.2. Overview

An overview of the relevant literature considered within this work can be found in Table 7. This contains a breakdown of the support structure, wind turbine and systems considered. Details of the domain analysis technique, objectives, constraints, design variables and optimisation algorithms are also provided as well as details of the software utilised in each of the works.

3.2.1. Literature overview

The paper by Clauss and Birk (1996) was one of the first which explored the optimisation of offshore Oil and Gas (O&G) platform geometries. The main aim of this work was to create an optimisation tool which could handle any platform geometry in order to reduce cost and maintain good seakeeping performance. The methodology was not described in detail in this work, making it difficult to compare some aspects of their model. Birk and Clauss (2008) follow on from Clauss and Birk (1996) however, in this work, experimental validation was carried out to prove that the hydrodynamic analysis carried out in WAMIT was accurate for the non-traditional hull shapes. A major focus in this work was the automated shape generation of the hull, which was modified to include a moonpool. Since the early work of Clauss and Birk (1996) and Birk and Clauss (2008) was for offshore O&G platforms, no considerations for the wind turbine were included in either optimisation. Similarly, mooring lines were also neglected. Unlike Clauss and Birk (1996) and Birk and Clauss (2008), Wayman (2006) produced the first work to perform an optimisation of the SPAR, Tension Leg Platform (TLP), and barge platform geometry for a 5 MW wind turbine. This work also considered the optimisation of the mooring lines, however, this was carried out in a separate optimisation. Sclavounos et al. (2008) focuses on the performance of the turbine, the weight, and the mooring line tension to find the optimal of the three platform classes for varying water depth.

Fylling and Berthelsen (2011) was the first to create an optimisation tool (WINDOPT) for SPAR platforms, including the mooring and power cable within the optimisation, determining how these aspects affect the overall shape of the platform when minimising cost and maintaining performance. Nordstrom et al. (2013) in 2013 created a similar tool but for the PelaStar TLP. This tool returns a set of optimal particulars and scantlings that represent the platform with the lowest cost of energy. The platform is then verified against standards. Similarly, Myhr and Nygaard (2012) focus on optimising the layout of the Tension Leg Buoy (TLB) and its mooring lines to reduce costs while considering the loads acting on the structure, which can cause excessive loading on the anchors. Myhr and Nygaard (2012) approach the TLB in a different manner, considering a space frame to try and reduce loads, rather than other works which consider a tubular floater. Like Wayman (2006), Myhr and Nygaard (2012) perform optimisations of the platform and

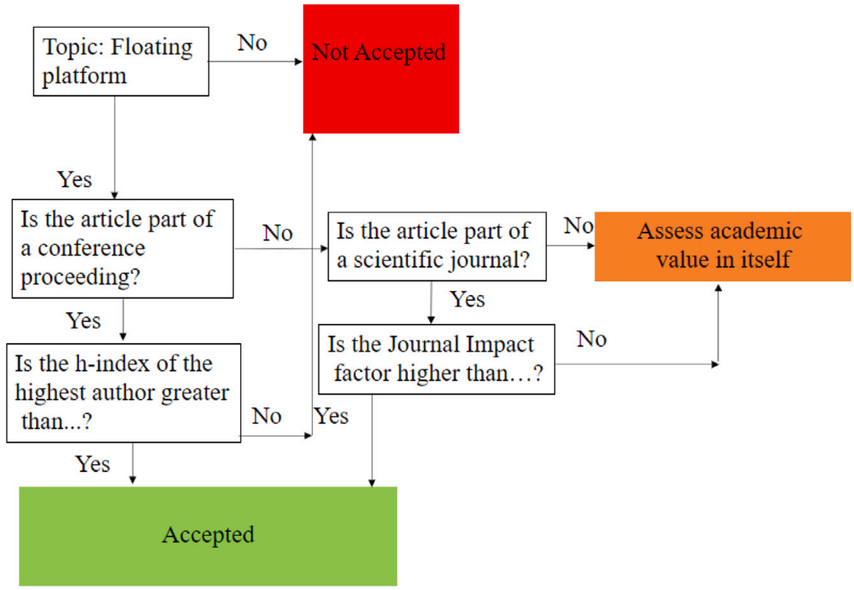

Fig. 1. Process for finding appropriate literature.

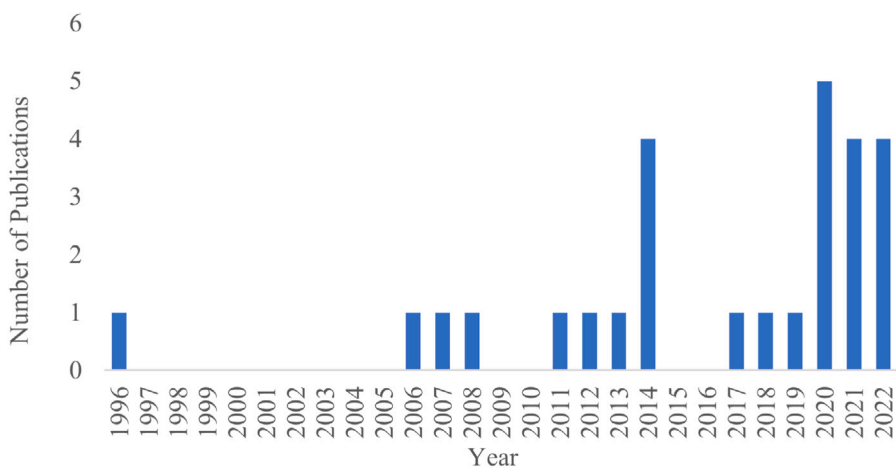

Fig. 2. Number of publications per year.

mooring lines separately in the time domain and the frequency domain, respectively. Similar to Myhr and Nygaard (2012) and Fylling and Berthelsen (2011), (Ferri et al., 2022) focus on only the semi-submersible platform, while the work carried out in 2022 by Ferri and Marino (2022) improve on their previous work by including a detailed cost model and an AEP model. Ghigo et al. (2020) presents six concepts. However, the optimisation result is only provided for the SPAR and Hexafloat platforms. Similarly (Ferri and Marino, 2022; Ghigo et al., 2020) also have a cost and AEP model presenting an end output value for the Levelised Cost of Energy (LCoE) for each platform. Sandner et al. (2014) and, more recently, Hegseth et al. (2020) also integrate multiple systems, with a strong focus on optimising the control system for three different SPAR platforms. Sandner et al. (2014) carry out the optimisation of three different SPAR geometries finding the most optimal controller gains to maximise power and reduce tower bending moment and inherently the nacelle acceleration, like a large percentage of other works seen in Section 3.3.

Hall et al. (2013) is one of the leading authors in this field, having published multiple articles. The work carried out in 2013 details an optimisation framework that includes the three main platform typologies, which can consider a wide range of existing and feasible non-existent platforms. Karimi et al. (2017) follows a very similar process to Hall et al. (2013) considering the three main platform stability classes, SPAR, TLP, and semi-submersible for a 5 MW wind turbine. This work resembles that of Hall et al. (2013) focuses on trade-offs between cost and performance. Hall et al. (2014) has a different approach to all other papers considering the hydrodynamic properties to express the support structure rather than making prior assumptions about the geometry with traditional geometrical design variables. This method removes the geometrical constraints and widens the design space. This work uses six generic support structure designs, which allows the hydrodynamic coefficient calculated to be compared to each support structure to determine their similarity.

Gilloteaux and Bozonnet (2014) do not carry out an optimisation as such, but it is the beginning of an optimisation process, a cylindrical body is modelled, and the hydrodynamics are assessed. From this assessment, four changes are made to the platform by adding one heave plate, two heave plates with different aspect ratio, and finally, three heave plates and active ballast. In essence, this is an optimisation that is not automated and over a smaller design space. Lemmer et al. (2020) also do not carry out an optimisation, it does however explore three semi-submersible designs with varying drafts to find the best solution.

Initial work carried out by Leimeister et al. (2019) uses an optimisation approach to determine a SPAR geometry for a 7.5 MW turbine

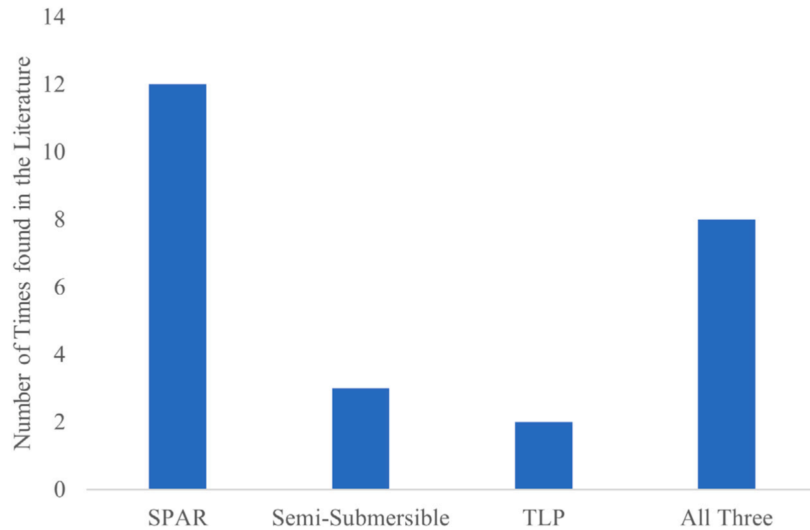

Fig. 3. Platforms optimised within literature.

based on the 5 MW turbine rather than using traditional up scaling methods, ensuring the platform is still stable. Leimeister et al. (2020, 2021) focus on implementing the optimisation of SPAR platforms into the Modelica library for Wind Turbines (MoWiT) model for a wide range of design load cases, Leimeister et al. (2021) including considerations for the blade shape to optimise power generation without increasing thrust and load on the structure.

In 2020, Hegseth et al. (2020) was one of the very few groups of researchers to consider not only the platform, but the combined platform, tower, mooring, and control system in the optimisation process. This allows the coupling effects between the tower and the platform to be considered. Dou et al. (2020) and Lemmer et al. (2020) also consider the control system, the work by Dou et al. (2020) add an extension to the optimal control parameters of the work by Hegseth et al. (2020). The work by Hegseth et al. (2020) and Dou et al. (2020) draw focus on optimising the SPAR platform whereas Lemmer et al. (2020) focus on a semi-submersible with heave plates.

In later work by Hegseth et al. (2021) the tower and SPAR were optimised to host a 10 MW wind turbine considering environmental effects, as well as the trade-off between CAPEX and OPEX based on fracture mechanics and updating reliability through inspection. Similarly, Leimeister and Kolios (2021) use a reliability approach for platform optimisation; By doing so, this addresses the issues of lack of standardisation, design standards, and over-engineered platform shapes. Bracco and Oberti (2022) also addresses design standards but instead focuses on optimising four main platform prototypes, considering the hydrostatics of each meet DNV design standards.

Benifla and Adam (2022) present a different platform typology, called Universal Buoyancy Body (UBB). Rather than using traditional stiffening methods, this platform has an inner and outer ‘pipe’ to strengthen the structure. Fig. 6 shows the structures’ geometry. It is predicted that this design will help reduce costs, by avoiding longer manufacturing times and complexities related to stiffeners. It is also expected that it could work in place of any cylindrical body in any of the three main platform typologies.

Fig. 3 highlights the platforms that have been worked on the most and how many papers include the three stability classes in their work. The majority of the research carried out has only considered a SPAR substructure. The reason for this is expected to be due to their simplicity for modelling purposes and the utilisation of a SPAR support structure at the Hywind site for a number of years. However, a large number of papers also considered all three platforms in their optimisation.

3.2.2. Turbine size

An improvement in Hegseth et al. (2020) compared to other work was the use of the 10 MW DTU wind turbine, compared to other work that only used the 5 MW NREL turbine (Hall et al., 2013, 2014; Karimi et al., 2017; Leimeister and Kolios, 2021; Leimeister et al., 2021, 2020; Sclavounos et al., 2008; Fylling and Berthelsen, 2011; Bracco and Oberti, 2022). Some of these papers, particularly (Bracco and Oberti, 2022; Leimeister et al., 2021, 2020; Leimeister and Kolios, 2021) were published in the last two years and still only use the smaller 5 MW wind turbine, making it difficult to compare with current industry turbines, and even more difficult for future floating wind farms with an expected turbine capacity of upwards of 15 MW (Global Wind Energy Council, 2021). Similarly to Hegseth et al. (2020) and Dou et al. (2020), Ghigo et al. (2020) carry out an optimisation for the 10 MW as well the 5 MW and wind turbines for six floating platform concepts allowing for a comparison between technologies. Dou et al. (2020), Lemmer et al. (2020) and Ferri et al. (2022) also recognised the need to use a larger turbine by optimising the SPAR platform and the semi-submersible platform, respectively, for the 10 MW DTU turbine, while both consider the mooring system. Pollini et al. (2021) are the only researchers who use the 15 MW wind turbine in their optimisation with a focus on the optimisation of the mooring system and the support structure of a SPAR in a very fast process that takes only a few minutes. This is a key tool for quickly analysing and comparing future sites given the drive in the industry to draw out the maximum power, using bigger turbines (Global Wind Energy Council, 2021). Pollini et al. (2021) are the most relevant in terms of turbine size since the industry is expanding so rapidly with the most powerful turbine prototype rated 14 MW already installed (General Electric, 2022). Fig. 4 below shows visually how little work has been done on any turbine greater than 5 MW.

3.3. Objective functions

An overall summary of the type of objectives used in the literature can be seen in Fig. 5.

Fig. 5 highlights that overall cost is the most predominant objective followed by the response. Cost is expected to be the main objective in the majority of engineering work and floating offshore wind is no different. The ability to find the cheapest yet feasible design option is crucial to help drive down the cost and, maintain high energy yield allowing FOW to be more competitive with other energy sources. In a lot of cases, there are conflicting objectives within the literature. The cost objective is used in work by Sclavounos et al. (2008), Fylling and

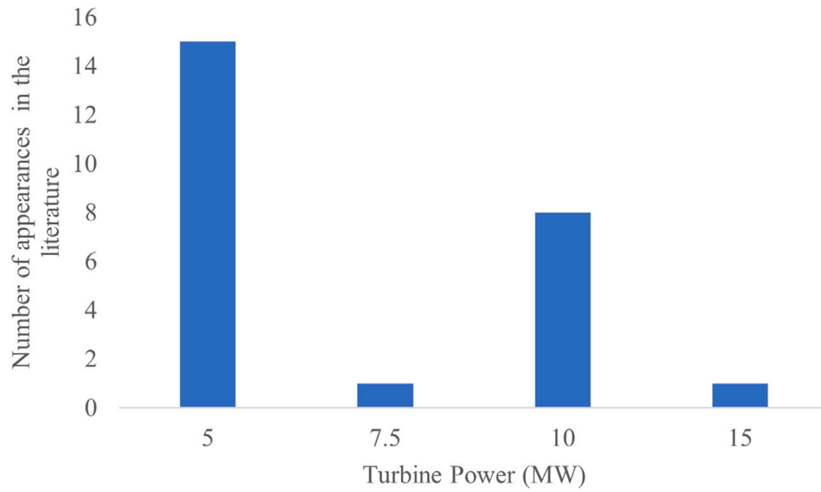

Fig. 4. Wind turbine power capacity used in existing literature.

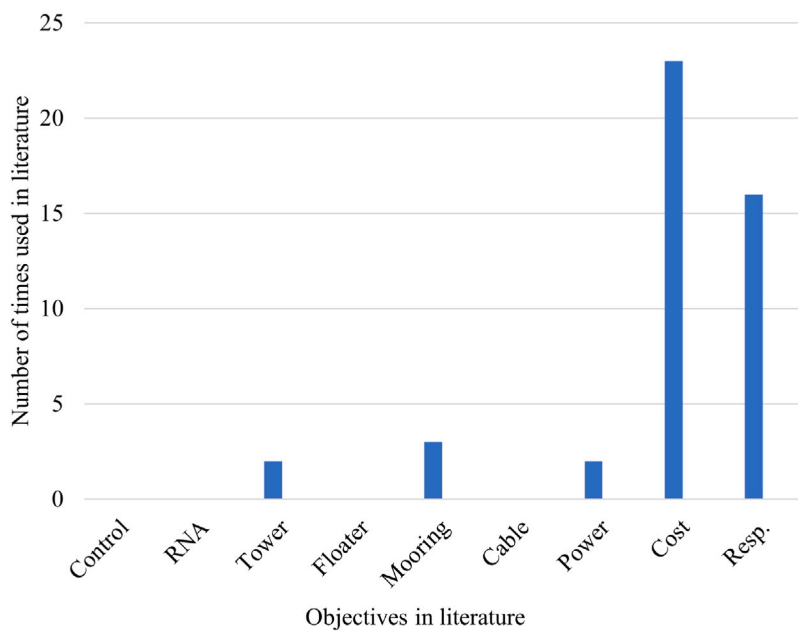

Fig. 5. Type of objectives used in the literature.

Berthelsen (2011), Myhr and Nygaard (2012), Hall et al. (2013), Karimi et al. (2017), Lemmer et al. (2020, 2017), Benveniste et al. (2016), Dou et al. (2020), Hegseth et al. (2020, 2021), Pollini et al. (2021), Hall et al. (2014), Leimeister and Kolios (2021), Wayman (2006), Birk and Clauss (2008), Ghigo et al. (2020), Leimeister et al. (2021, 2020), Pillai et al. (2018), Zhou et al. (2021) and Ferri and Marino (2022). The platform response was used as an objective in Sclavounos et al. (2008), Hall et al. (2013), Karimi et al. (2017), Ferri et al. (2022), Ferri and Marino (2022), Hall et al. (2014), Leimeister et al. (2021), Clauss and Birk (1996), Wayman (2006), Sandner et al. (2014), Leimeister et al. (2019), Gilloteaux and Bozonnet (2014), Birk and Clauss (2008), Ghigo et al. (2020), Leimeister et al. (2021, 2020) and Pillai et al. (2018). The power production (Hegseth et al., 2020; Sandner et al., 2014), mooring (Sclavounos et al., 2008; Myhr and Nygaard, 2012; Brommundt et al., 2012) and tower systems (Lemmer et al., 2017; Benveniste et al., 2016) were considered less frequently in the objective function.

3.3.1. Cost objective

Fylling and Berthelsen (2011) has one of the most adopted objectives, aiming to minimise the cost of the platform, of the mooring lines, and of the power cable. Similarly, in Karimi et al. (2017) the objective is to minimise the cost of the platform and the mooring system. The main objective in Myhr and Nygaard (2012) is to try and reduce the loading on the structure, which in turn will help reduce structural and station keeping system maintenance costs.

Bracco and Oberti (2022) and Ghigo et al. (2020) focus purely on minimising the material cost of the different platforms. Dou et al. (2020), Benifla and Adam (2022) and Pollini et al. (2021) use platform mass and mooring line minimisation as the objective. Hegseth et al. (2021) share the same objective as the above articles to minimise cost, in their case for the platform and tower. Wayman (2006) sets the objective to minimise the surface area of the cylinder, by doing so the volume and therefore the mass of steel required will be reduced, leading to a reduction in material cost. Sclavounos et al. (2008) consider the weight of the platform and the dynamic tension of the mooring line to find the optimal platform. This paper highlights that a reduction in weight will lead to a reduction in platform cost. This is consistent within all of the literature considered. Like in many other papers presented, Hegseth et al. (2020) consider the reduction in cost as a sub-objective along with the power quality of the turbine expressed as the rotor speed standard deviation. Both parameters are combined into one main objective function. Each sub-objective is given a weighting, which combined will equal one. The weighting of each is varied to determine the importance of each sub-objective. Hall et al. (2013) and Karimi et al. (2017), share the same multi-objectives: to minimise cost and nacelle acceleration, similarly to Hegseth et al. (2020) weightings are added to each sub-objective.

3.3.2. Motion objectives

The nacelle acceleration is the other competing objective in Karimi et al. (2017) and Hall et al. (2013) with the goal to minimise this parameter due to the platform's pitch and surge motions. The purpose of this is to avoid excessive loads or higher fatigue damages on the blades and on the drive train, leading to a decreased system life span.

Both Hall et al. (2013), Karimi et al. (2017), Sclavounos et al. (2008) and Hall et al. (2014) only consider the nacelle acceleration in the objective function. It is assumed that Hall et al. (2014) focus on this single objective function due to the use of hydrodynamic properties to determine the geometry. The rationale given is that it would be difficult to set cost as the objective when geometric values such as length, thickness, and diameter are not available in the optimisation process.

Leimeister and Kolios (2021), Leimeister et al. (2019) have objectives to minimise the horizontal displacements (i.e., surge, sway, and yaw) of the system, due to restrictions on the power cable motion. The overall goal of the work carried out by Leimeister and Kolios (2021) is to find the most reliable structure design. This has been done by considering the limit state of the bending stress at the tower base and the tensional stress of each mooring line, which are linked to the platform dynamic response to the metocean conditions, and hence also linked in turn to the platform geometry. Leimeister et al. (2021, 2020) objectives were to minimise the angle of inclination, reduce nacelle acceleration, and minimise translational motion, with the overall objective of reducing mass and cost. The reason for these objectives was based on the fact that the OC3 SPAR considered in their work has very high safety factors.

Work by Clauss and Birk (1996) for O&G platforms aimed to minimise the double amplitude of various forces and motions to stop disruption of platform operations. Similarly, Birk and Clauss (2008) had the objective to reduce the double amplitude of the heave motion along with the heave resonance. This can be done by increasing the draft of the platform and reducing the waterplane area, the motions will also be decreased. However, this is expected to also have a knock-on effect increasing cost of construction and installation, along with difficulty to handle this geometry which is not considered in the optimisation process. Both pieces of work by Clauss and Birk (1996) and Birk and Clauss (2008) are not for floating offshore wind however are still important and valuable when determining which platform is most suitable to meet a specific objective. Ferri et al. (2022) had the objective to minimise the amplitudes of the surge, heave, and pitch Response Amplitude Operator (RAO) at their respective eigenfrequencies. More recent work by Ferri and Marino (2022) have slightly different objectives, aiming to reduce the fatigue damage in certain load cases, maximum stress on the tower, and overall cost. These objectives are hoped to extend the service life and reduce the LCoE.

As mentioned earlier, Gilloteaux and Bozonnet (2014) and Lemmer et al. (2020) do not carry out optimisations however, similar to most other work, the objective within Gilloteaux and Bozonnet (2014) is to maintain stability. Whereas the objective in Lemmer et al. (2020) is to maximise power, by tuning the controller gains and minimise nacelle acceleration and cost.

3.4. Constraints

In order to ensure the optimisation results are within the realms of reality, it is important that constraints are added to the process. The most common constraints added within the literature are nacelle acceleration, platform motion, design variables, stability, mooring and structural. All of which are discussed within this section.

3.4.1. Cost constraints

Cost is one of the main drivers within all industries, and it has been made clear that floating offshore wind is no exception; for this reason, Hall et al. (2013) adopted a cap of $9 million (2013 USD) on the support structure. This constraint was only seen three times in the literature, and the purpose of the constraint is unknown. It is speculated by the author that its purpose is to remove economically unfeasible design solutions. Karimi et al. (2017) has the same constraint on cost but includes additional constraints on performance, and design variables, these can be seen below in Table 7. Ferri and Marino (2022) apply a constraint on the cost of €8.15 Million (2022 EUR) and the tower bending moment, the purpose of this constraint is to avoid contradictory results with respect to the ultimate load state optimisation.

All other work considered in this review does not include a cost constraint, but Fylling and Berthelsen (2011), Karimi et al. (2017), Bracco and Oberti (2022), Ghigo et al. (2020), Hegseth et al. (2020, 2021), Dou et al. (2020), Benifla and Adam (2022), Pollini et al. (2021), Wayman (2006) and Sclavounos et al. (2008) consider it as an objective in their work. Ferri et al. (2022) is the only study which imposes that the mass of the 10 MW platform and mooring system should not be greater than the upscaled 5 MW basis platforms and mooring system. The purpose of this constraint is to seek a cost reduction and avoid over-engineering.

3.4.2. Nacelle acceleration constraints

The nacelle constraints which were applied in the literature can be seen below in Table 1

Design Load Case (DLC) 1.1 is for normal power production at around rated wind speed, DLC 1.3 is for below, at, and above rated wind speed with an extreme turbulent model, and DLC 1.6*a* is also below, at, and above rated wind speed in a severe sea state. Additionally in Leimeister et al. (2019) DLC 1.6*b* was also considered which is parked operation in extreme wind model, and extreme sea state model both with 50 year recurrence period. Pollini et al. (2021) use DLC 1.2 for a wind turbine operating in normal conditions. Since Leimeister and Kolios (2021), Leimeister et al. (2021, 2020, 2019) and Pollini et al. (2021) cover a larger range with more harsh operating conditions, the use of a more relaxed allowance on the maximum nacelle acceleration is understandable. Fylling and Berthelsen (2011) and Gilloteaux and Bozonnet (2014) both have a larger acceptable nacelle acceleration this is expected since it considers operational and survival load cases.

A number of papers consider the nacelle acceleration as a constraint since it is expected that it can cause damage too equipment, create large platform motions, is thought to reduce the lifetime, induce higher flap wise bending moments, reduce turbine performance and hence power production. It has however been argued by Nejad et al. (2019) that the nacelle acceleration is not correlated to the drive train response and does not affect the power production, so long as the pitch controller remains operational. It was also predicted by Nejad et al. (2019) that the main bearing fatigue is also not affected by the nacelle acceleration. These findings cause the author to question the use of this constraint in the optimisation framework. It would be interesting to see if the nacelle acceleration affects other parts of the turbines fatigue life, such as the tower, support structure and mooring lines. The work by Nejad et al. (2019) only considers a 5 MW turbine, since the tower height increases with turbine since the author wonders if there is still no affect on the drive train and the main bearing due to the acceleration of the nacelle.

Table 1
The nacelle acceleration constraints applied within the current literature.

Ref	Nacelle acceleration limit (m/s^2)	Operating condition
Karimi et al. (2017)	1	Below, at, and above rated wind speed, and normal wave operating conditions.
Leimeister and Kolios (2021), Leimeister et al. (2021), and Leimeister et al. (2020)	1.962	IEC standard 61400-3-1, Design load case (DLC) 1.1, 1.3 and $1.6a$
Leimeister et al. (2019)	1.962	IEC standard 61400-3-1, DLC 1.1, 1.3, $1.6a$ and $1.6b$
Pollini et al. (2021)	1.962	IEC standard 61400-3-1, DLC 1.2
Dou et al. (2020)	2	IEC standard 61400-3-1, DLC 1.2
Fylling and Berthelsen (2011)	2.6	Operational and survival load cases
Gilloteaux and Bozonnet (2014)	5	Normal operating condition and survival condition

3.4.3. Motion constraints

When considering motion constraints the simplest is to impose a constraint on the static pitch. This can easily be improved by considering both static and dynamic pitch for a number of operational cases. This constraint is important because after a certain angle the turbine would become unstable but it would also allow the reduction in power to be considered. Other constraint on other degrees of freedom can also be considered to ensure the platform is not moving more than acceptable limit ensuring the mooring lines and dynamic cable are not under severe loading. The final motion constraint generally considered is the natural period/frequency, which helps avoid resonance and potential failures of the system as a whole. In the extensive work by Leimeister and Kolios (2021), Leimeister et al. (2021, 2020, 2019) to achieve the required wind turbine performance, total inclination angle of the floating structure must be less than 10 degrees. Both consider a number of normal operational conditions and extreme events. Karimi et al. (2017) and Sclavounos et al. (2008) both consider the static pitch angle should be less than 10 degrees, both consider normal operational conditions only. Work completed by Ghigo et al. (2020), Ferri et al. (2022) and Ferri and Marino (2022) impose stricter constraints, requiring the maximum static pitch angle to be less than 5 degrees, for both normal and extreme conditions. This choice is probably due to the fact that the platform dynamic response is neglected in their work. Pollini et al. (2021) require the static pitch and surge to be less than 8 degrees and 50 m, respectively. Dou et al. (2020) also apply a maximum static surge motion of 50 m to the platform. When considering only the static pitch having a lower constraint seems like a fair assumption given there is no environmental loading considered.

It is beneficial to consider both dynamic and static pitch as a summation since the static position will be the equilibrium for the system. Combining the static position with the dynamic displacement helps to simulate the real life event or potential phenomenon more accurately. Gilloteaux and Bozonnet (2014) consider the summation of static and dynamic pitch should be less than 10 degrees, whereas Dou et al. (2020) consider dynamic and static pitch individually, imposing that each should be less than 10 degrees. The work by Gilloteaux and Bozonnet (2014) deal with extreme and normal operating conditions, whereas Dou et al. (2020) only consider normal operating conditions, making their constraints more relaxed in comparison to Gilloteaux and Bozonnet (2014). Hall et al. (2013) also include a similar constraint, the static pitch angle in this work has a 10 degree limit and separately the dynamic pitch plus the standard deviation of the pitch must be less than 10 degrees.

Hall et al. (2013), similar to Dou et al. (2020), only examine normal operating conditions, making the consideration of a degree limit seem fair. Fylling and Berthelsen (2011) apply a constraint on the dynamic pitch of the platform, requiring the inclination of the tower to be less than 9 degrees, for both normal and extreme conditions. Hegseth et al. (2020, 2021) apply a 15 degree constraint on the combined static and dynamic pitch angle in the 50-year survival condition. Since this is for a survival condition it makes sense for it to be higher than other literature.

A more flexible approach which is considered in the following paragraph, considers the motion as a percentage of water depth, since a displacement may seem large dependent on how deep or shallow the water depth is. Leimeister and Kolios (2021), Leimeister et al. (2019) constrain the mean translational motion to not exceed 20% of the water depth in normal and extreme conditions, whereas Hegseth et al. (2020) set a maximum constraint of 32 m on the offset in the 50-year condition. Applying a similar constraint to Hegseth et al. (2020), Ferri et al. (2022), Ferri and Marino (2022) state that the admissible platform offset to water depth ratio must be less than 0.15 (i.e. 15% of the water depth). Both normal and extreme load cases were considered in Ferri et al. (2022), Ferri and Marino (2022). Considering this constraint as a percentage of water depth is a more flexible approach, making it suitable for multiple different sites.

Both the heave and pitch periods are required to be within a given range in Fylling and Berthelsen (2011), to avoid resonance with typical wave load periods. Building on the work in Fylling and Berthelsen (2011), Dou et al. (2020) also include these constraints along with the maximum surge frequency. It was however noted that Birk and Clauss (2008) only consider the heave period. Hegseth et al. (2021) also only consider the heave period applying a lower limit of 25 s to avoid resonance with the wave period. Lemmer et al. (2020) only considered a constraint on the pitch natural frequency, the reason for this is the strong focus on the effect of the controller, since it is related to reducing torque and thrust, it will also effect the motion of the platform in the pitch direction. Similarly Pollini et al. (2021) also apply constraints to the eigenvalues, however in this case three Degrees of Freedom (DOF) are considered.

3.4.4. Design variables constraints

It is common practice to include constraints on design variables, Bracco and Oberti (2022) along with Hall et al. 2013, Karimi et al. 2017, Leimeister and Kolios 2021, Clauss and Birk 1996, Sclavounos et al. (2008), Leimeister et al. (2021, 2020), Hegseth et al. (2020), Birk and Clauss (2008), Ghigo et al. (2020), Leimeister et al. (2019), Lemmer et al. (2020), Pollini et al. (2021), Ferri et al. (2022) and Hegseth et al. (2020) include such constraints on the design variables. This removes unrealistic designs and creates a more focused design space. Birk and Clauss (2008) highlight that the purpose of the diameter constraints is to ensure the platform can be transported and removes restrictions during the construction phase. Dou et al. (2020) only apply an allowable range for the mooring line length, which would probably need to change for each site investigated since water depth varies. Perhaps taking into account the maximum mooring line length as a % of water depth would make the work more universal for different site conditions. This is also the only work to consider the maximum percentage of the suspended line.

The constraints imposed on the design are directly linked to the individual components considered in the work. For example Hegseth et al. (2021) include the tower in their optimisation and therefore, a constraint is set to ensure that the bottom of the tower and the top of the SPAR have the same diameter and thickness. The hull taper angle is also limited to a maximum value of 10 degrees to avoid shapes where the physics is not captured correctly (Hegseth et al., 2021). Since Birk and Clauss (2008) proved with experimentation that WAMIT can correctly capture hydrodynamics of strange shapes, perhaps this constraint is not required for this purpose but maybe for the manufacturability of the structure.

As discussed, in Section 3, Hall et al. (2014) takes a different approach than other works reviewed, and therefore also takes a unique approach in terms of variable constraints. As explained before Hall et al. (2014) consider hydrodynamic performance coefficients rather than traditional geometrical values to describe the platform geometry. For this reason, a collection of unique geometrically-defined platforms are used as basis designs, from which the hydrodynamic performance coefficients can be linearly combined to approximate the characteristics of any platform in the design space. Constraints are applied to the performance coefficient to a range between zero and one, and the summation of the variables must equal one. The reason for a range of zero to one is the coefficients of each basic design are scaled and superimposed to find the new coefficients for each design. If the coefficients are summed equal to one then the platform geometry is known, however, if it equals zero then the optimisation tool has no bearing on the platform configuration This work does not explicitly state the constraints they used, however, it is noted that the constraints are on the hydrodynamic design properties. This suggests that there are bounds on parameters such as stiffness, damping, and added mass matrix etc.

3.4.5. Static stability constraints

Bracco and Oberti (2022) differ slightly from other work, as the constraints are related to the DNV design standards DNVGL-ST-0119 for the free-float condition, minimum freeboard, and the DNV-OS-C301 standard for the maximum intact inclination angle under normal and survival conditions. These constraints are good because, the designed platform will need to pass this criteria in order to get certification. Sclavounos et al. (2008) consider a minimum restoring coefficient to ensure adequate restoring under the towing condition and operation, similar to the free float constraint in Bracco and Oberti (2022). Clauss and Birk (1996) have constraints on floating stability of the O&G platform, but do not explicitly state what they are. Fylling and Berthelsen (2011) apply a limit on the SPAR draft as the only constrained design variable, leaving a much wider design space. Work in Gilloteaux and Bozonnet (2014), Ghigo et al. (2020) also constrains the draft but additionally sets a minimum value on the metacentric height, Birk and Clauss (2008) also constrain the metacentric height. Additionally, Ghigo et al. (2020) place a minimum freeboard requirement which would be something design standards would require like Bracco and Oberti (2022) inclusion of DNV standards. In Dou et al. (2020) and Pollini et al. (2021) a simple constraint related to hydrostatics was used to ensure that the centre of buoyancy is higher than the centre of mass. Benifla and Adam (2022) require the buoyancy to be above a particular value, depending on the type of platform.

It is unclear what constraints were actually set in Wayman (2006), however from the work it can be seen that for the SPAR, Trifloater, and Barge there needs to be a minimum restoring coefficient for the pitch degree of freedom, since both the SPAR, Trifloater, and barge should be able to maintain stability without mooring lines. These listed platforms are also required to have a realistic draft in order to remain below the waterline and in the SPARs case provide sufficient restoration. Wayman (2006) require the TLP to remain below the water line to reduce structural loading.

A slightly different perspective was applied in Sclavounos et al. (2008), where a constraint was added to the elevation of the free surface, ensuring that it does not exceed the draft of the cylinder when it is heeled, ensuring the support structures remain submerged. This constraint could also be useful to ensure that the minimum freeboard requirement is met.

3.4.6. Mooring line constraints

Mooring line constraints were also considered in Karimi et al. (2017) where they require that the tension remains relatively constant for taut mooring lines, the standard deviation of the tension in the mooring line, cannot be greater than a third of the overall tension. Hall et al. (2013) also use the same constraint for the mooring lines. The mooring constraint in Wayman (2006) is related to the mooring line tension, they must provide sufficient restoring in the surge, and the tension of the windward tether must never exceed the maximum allowable tension, and the leeward tension cannot fall below the minimum allowable tension. Myhr and Nygaard (2012) apply mooring line constraints, which are considered by a penalty function on the cost function. Constraints were also applied to the natural periods for the optimisation of the mooring lines, to avoid natural periods of the rotor etc. Within Myhr and Nygaard (2012), as previously explained, the mooring and structure optimisation are in two separate domains. The constraints for the mooring line optimisation, in the time domain, are the following two: minimum tension required in a storm event, and the maximum axial stress in the space frame. Both Sclavounos et al. (2008) and Hegseth et al. (2020) apply similar constraints to the mooring line, stating that the dynamic line tension cannot exceed the breaking load of the mooring line, with Sclavounos et al. (2008) applying a safety factor of two. Pollini et al. (2021) set a constraint on the maximum vertical force to which the fairlead is exposed. They also require the mooring line length to fall within a prescribed range. This range will need to change depending on the depth of the water at the site. Fylling and Berthelsen (2011) have more constraints on the mooring line which are: maximum and minimum tension on the mooring line segment, minimum fatigue life, and maximum slope angle at the anchor. Constraints are also applied to the power cable, maximum tension, minimum cable curvature radius, maximum horizontal offset, and minimum static horizontal pretension limit. Ferri et al. (2022) apply cable length constraints, to ensure the triangular shape and the minimum amount of cable on the sea bed.

3.4.7. Structural constraints

The inclusion of structural constraints in limited within the literature, only appearing in the work of Hegseth et al. (2020, 2021) and Leimeister and Kolios (2021). Hegseth et al. (2020) focus on the constraints related to fatigue and the ultimate limit state for the SPAR and the tower, Table 7 details these constraints applied. Similarly, Hegseth et al. (2021) impose that the support structure fatigue damage must be less than a given value for the design fatigue factors. Other work which considers a structural constraint is Benifla and Adam (2022), placing a constraint on the maximum allowable stress over the complete platform structure.

Leimeister and Kolios (2021) have two main constraints related to the bending stress at the base of the tower and the tensional stress of the mooring line. These constraints ensure the tower base and mooring lines do not exceed the ultimate values (Leimeister and Kolios, 2021).

3.5. Design variables and platform modelling

3.5.1. Platform design variables

In Karimi et al. (2017) and Hall et al. (2013), a parameterisation scheme, able to describe the three main platform configurations (i.e., barge/semi-submersible, SPAR, and TLP) is used, consisting of nine design variables. Sclavounos et al. (2008) use five design variables, two of which describe the TLP, SPAR, and Barge platforms and three to describe the station keeping system. Authors of Hall et al. (2014) use a slightly different parameterisation scheme: rather than using values to describe the geometry, such as diameter or length, hydrodynamic properties are used.

Clauss and Birk (1996) firstly use a parameter which determines which O&G platform type is considered: gravity base, TLP, caisson semi-submersible, or semi-submersible. Then, for each different platform, different design variables are adopted. In the work by Birk and Clauss (2008), the SPAR geometry is described by four cylindrical sections which make up the full platform geometry. In order to express the SPAR geometry, the ratio of the two cross sectional areas where two sections join together, the length of each cylindrical section, and the ratio of each sections length compared to the next section and the total draft are used.

Bracco and Oberti (2022) consider four different platform types: SPAR, Windfloat Pelastar and Windstar. However, their work does not use a parameterisation scheme, and each support structure geometry has its own design variables. For example, the SPAR is expressed by the diameter, height, seawater height and ballast height, whereas the Pelastar is described by column height, diameter of hull and column, hull depth, arm radius, and concrete volume. Similarly to Bracco and Oberti (2022), Ghigo et al. (2020) present the SPAR and Hexafloat separately with their own design variables. This method limits the design space and removes the ability to explore other geometries and concepts, which would be useful in the initial design stages, particularly so for a less mature industry. Wayman (2006) optimise the barge and SPAR together because both are represented as cylindrical bodies, and the TLP and Trifloater are optimised separately with their own design variables. Leimeister and Kolios (2021), Leimeister et al. (2019) only explore one platform type, the SPAR, describing it with three design variables. Dou et al. (2020) also only consider the SPAR, but six design variables are used, three to identify the SPAR geometry, two for defining the station keeping system, and one for the export cable length. This is a similar approach to Pollini et al. (2021), focusing on the SPAR, and using six design variables, three for the SPAR geometry, and three for the station keeping system. Myhr and Nygaard (2012), similarly to the above, consider only one type of platform, a TLB. This work, however, adopts a ten variables design vector, four of which are related to the station keeping system, and the rest dedicated to identify the platform geometry. Ferri et al. (2022), Ferri and Marino (2022) and Lemmer et al. (2020) focus only on the semi-submersible platform configuration, Ferri et al. (2022) describe the hull geometry with five design variables, and its mooring system with two design variables. None of these design variables describes the geometry of the platform's bracings, whereas Lemmer et al. (2020) uses nine variables to describe the platform geometry, which does include the bracing. A parameter included in this work that has been rarely seen in the literature other than (Hegseth et al., 2020, 2021; Zhou et al., 2021) is the thickness of the steel. This is rarely seen in the literature due to the lack of structural considerations in the optimisation frameworks reviewed.

Fylling and Berthelsen (2011) include slightly more variables for the SPAR body compared to the aforementioned work, the main difference in this work is the SPAR is split into a number of cylinders, sometimes referred to as parts or segments. The thickness and diameter of the bottom plate are also considered, which can act as a damping plate by increasing the vertical drag force and added mass. This gives a total of five variables to describe the hull geometry, two of these variables, the length and diameter, are vectors describing how the geometry changes along the length of the SPAR. Hegseth et al. (2020) are one of the few groups of researchers who include in the design variables the geometry of the ring stiffeners inside the hull (each one described by five design variables, i.e. the thickness and length of the web and the flange, and the distance between the stiffeners). Since, in Hegseth et al. (2020), the tower does not include stiffeners, a higher density of steel is used to account for additional mass related to the stiffeners. The geometry of the SPAR hull and tower shells are expressed by vectors for the diameter and the thickness. Similar to Fylling and Berthelsen (2011), Hegseth et al. (2020) consider both the tower and the SPAR as a number of truncated cones rather than cylindrical segments creating a 'smoother' geometry. Additionally, the SPAR hull considers the overall length as a variable, unlike the tower, which is kept constant to ensure the correct hub height. Hegseth et al. (2020), unlike the approaches in the other works, include variables for the controllers that allow the proportional and integral gain to be optimised to get the maximum energy output. It can be clearly identified that Hegseth et al. (2020) consider the largest number of variables, totalling 110. A method to reduce this number was to consider a B-spline for the ring-stiffener parameters, which uses a pre-defined number of control points to produce a smooth distribution of parameters. Overall this reduced the variables to 80. The work carried out in 2021 by Hegseth et al. (2021) uses the same constraints minus the scantling and controller design variables.

3.5.2. Platform geometry

Work by Benifla and Adam (2022) presents a support structure called Universal Buoyancy Body (UBB) aimed at reducing production cost by serialising the fabrication procedure using standard components. In Fig. 6, a visual representation is reported.

It is expected that because it is expressed with cylindrical bodies joined by bracings it can represent many different platform typologies since in general terms most support structures comprised of cylinders. Unlike the work of Hegseth et al. (2020), which considers the scantling, Benifla and Adam (2022) use an inner and outer cylinder which can both be expressed by length, thickness, and radius. It is hoped that this design will reduce the manufacturing cost by reducing the material and production costs since traditional stiffeners are not used. The strength of the structure will be provided by using thicker plates to create the inner and outer cylinders. The author does however wonder if this research has considered that by increasing the thickness of the steel plates, the difficulty to form plates into cylinders increases and often more sections are required to make the cylinder to avoid difficulties in rolling. As the thickness of plates increase the number of v-grooves required also increases for the welding process, causing the weld cost to increase. When considering this it would be interesting to draw a comparison on the cost of a traditional stiffening structure compared to this new proposed structure.

Authors of Karimi et al. (2017), Hall et al. (2013), Dou et al. (2020), Pollini et al. (2021), Ferri et al. (2022), Ferri and Marino (2022), Wayman (2006) and Benifla and Adam (2022) present the platforms in their work using right circular (i.e., straight sided) cylinders, therefore not considering any changes in radius along the vertical direction in the single cylinder (although different cylinders may have different radii). Authors of Hall et al. (2014) and Bracco and Oberti (2022) also use multiple cylinders to describe the geometry of the different platforms. Similarly, Ghigo et al. (2020) use a right circular cylinder to describe the SPAR hull, and a number of the same elements to describe the Hexafloat platform. The cylinders are not split into a number of smaller cylinder segments, and they can only change the overall diameter and length during the optimisation process. The work presented in Sclavounos et al. (2008) only considers singular, straight sided cylindrical bodies and does not include any additional appendages, such as bracing or legs, making the geometry simplified. The work by Leimeister et al. (2018, 2020, 2019) also present the platform in a simplistic manner, only modelling the complete vertical section of the SPAR: similarly to Karimi et al. (2017), Hall et al. (2013) and Hall et al. (2014) it does not consider the cylinders segmented into a number of smaller segments or changes in radius. A more advanced modelling approach was adopted by Fylling and Berthelsen (2011): the SPAR is divided into segments, where each segment can have a different radius. In a real scenario, it is more realistic to consider the support structure is constructed from multiple parts, since the platform would be made from a number of segments in order for it to be manufactured. It could, however, be argued in this case that it is less realistic since the radius of each cylinder is different, and it will be more difficult to manufacture. Clauss and Birk (1996) use horizontal cross sections which could be meshed together, allowing the radius to change vertically, giving a curved body unlike the stepped shape in Fylling and Berthelsen (2011). Hegseth et al. (2020, 2021), differently from the others, but similar

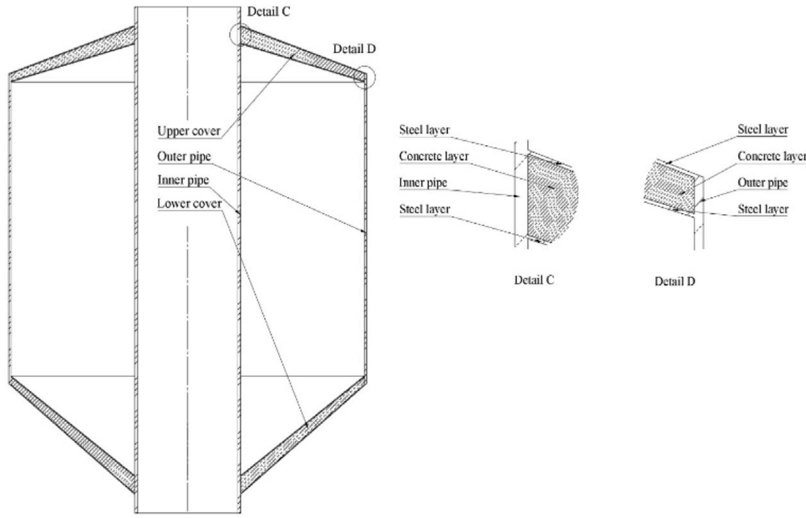

Fig. 6. Universal Buoyancy Body from Benifla and Adam (2022).

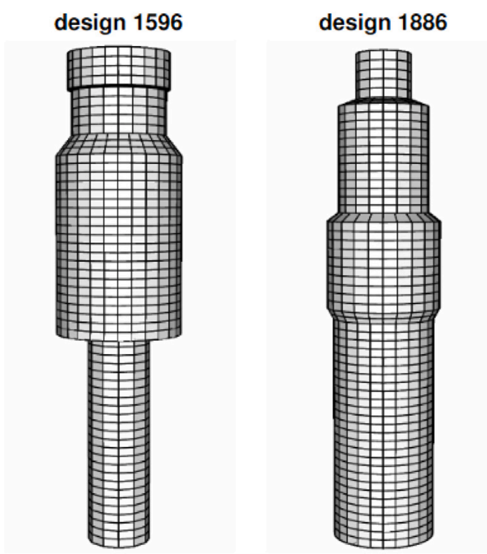

Fig. 7. SPAR support structure proposed in Birk and Clauss (2008).

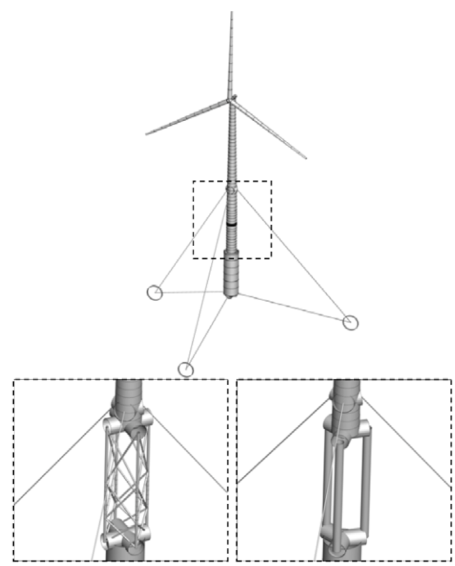

Fig. 8. Space-frame concept utilised in Myhr and Nygaard (2012).

to Clauss and Birk (1996), describe the platform and tower geometry with truncated cones rather than right circular cylinders. Birk and Clauss (2008) propose a parameterisation scheme for the SPAR, The SPAR body consists of four vertical-sided columns and three truncated cones to join the vertical columns. The radius of each column can have a different value hence the requirement for the truncated cones to join each section. Fig. 7 shows examples of the proposed SPAR support structure.

Myhr and Nygaard (2012) utilise a space-frame which differs from other work done in this area, see Fig. 8. There are four variables which change the geometry, the outer diameter of the lower cylinder, height of the space-frame, distance between column and turbine centre line and the outer diameter of the vertical column(s) in the space-frame. The purpose of using this geometry is by replacing the cylinders it is expected that the wave forces will be reduced a significant amount as well as reduce the fabrication costs.

3.5.3. Mooring line design variables

Fylling and Berthelsen (2011) identify the mooring lines' and power cables' geometry with the following variables: line direction, pretension, segment length, diameter, and net submerged weight. Sclavounos et al. (2008) use three variables to describe the mooring system, considering the angle between the free surface and the anchor, allowing the type of mooring system to be determined, i.e., taut or catenary. Hegseth et al. (2020) also model the mooring line, using the diameter of the line, the depth of the fairlead below the waterline, the total length of the line, and the horizontal distance between the fairlead and anchor. Since different platforms may require different mooring configurations, Karimi et al. (2017) and Hall et al. (2013) use one of the variables to identify which mooring arrangement is used.

3.6. Optimisation algorithms

This section focuses on the optimisation algorithms used within the current literature, these different techniques will be briefly explained, for further details on trends within see Younis and Dong (2010). Fig. 9 highlights the algorithms used graphically, where it can be easily identified that genetic algorithms are used the most. Authors of Benifla and Adam (2022), Bracco and Oberti (2022), Ferri et al. (2022), Leimeister et al. (2020, 2021), Ghigo et al. (2020), Birk and Clauss (2008), Leimeister et al. (2019), Karimi et al. (2017), Hall et al.

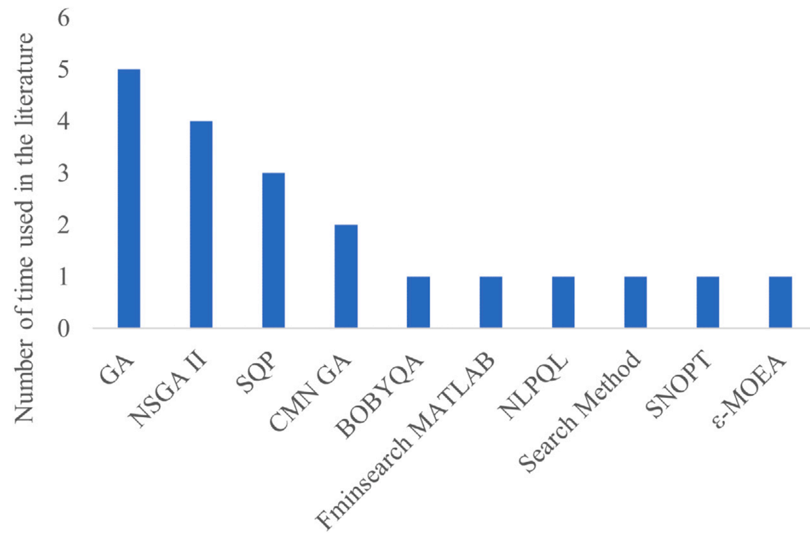

Fig. 9. Optimisation algorithms used within the literature.

(2013) and Ferri and Marino (2022) all use GA optimisation techniques. Further information on genetic algorithms can be found here (Mitchell, 1998). The gradient-based methods used in Hegseth et al. (2020), Hall et al. (2014), Clauss and Birk (1996), Pollini et al. (2021), Dou et al. (2020), Fylling and Berthelsen (2011), Myhr and Nygaard (2012) and Hegseth et al. (2021) make use of functions gradients to search for the optimal design, seeking out the 'turning points' of the objective function and constraints in a given design space to find the global maximum or minimum depending on the goal.

Several authors use a multi-objective Genetic Algorithm (GA) tool to find the optimal platform (Karimi et al., 2017; Ghigo et al., 2020; Bracco and Oberti, 2022; Ferri et al., 2022; Ferri and Marino, 2022; Benifla and Adam, 2022). Hall et al. (2013) use a cumulative multi-niching GA (CMN GA). Leimeister and Kolios (2021), Leimeister et al. (2021, 2020) and Leimeister et al. (2019) use the Non-dominated sorting GA II (NSGA II) from Platypus. Clauss and Birk (1996) utilise a nonlinear programming algorithm. Similarly, Fylling and Berthelsen (2011) adopt a Non-Linear Programming technique, Quadratic Lagrangian (NLPQL) optimisation. Hall et al. (2014) also use a non-linear optimiser found in the MATLAB toolbox, 'fminsearch'. Myhr and Nygaard (2012) apply a Bound Optimisation BY Quadratic Approximation (BOBYQA). Hegseth et al. (2020, 2021) use a gradient-based method (SNOPT) that uses sequential quadratic programming. Similar to Hegseth et al. (2020), Dou et al. (2020) also use a sequential quadratic programming (SQP) method. Birk and Clauss (2008) utilise a multi-objective evolutionary algorithm (MOEA).

Unlike other works, Pollini et al. (2021) use two optimisation techniques, the first for a global solution and the second for a localised optimisation. The first stage of optimisation uses SQP and the latter uses relaxation-induced neighbourhood search (RINS). Authors of Wayman (2006) and Sclavounos et al. (2008) do not state which optimisation algorithm is used.

3.7. Modelling and software utilised

A number of papers use frequency domain dynamic models, due to the smaller computational time to carry out the analysis (Karimi et al., 2017; Hall et al., 2013, 2014; Fylling and Berthelsen, 2011; Myhr and Nygaard, 2012; Sclavounos et al., 2008; Hegseth et al., 2020; Gilloteaux and Bozonnet, 2014; Birk and Clauss, 2008; Dou et al., 2020; Pollini et al., 2021; Ferri et al., 2022; Ferri and Marino, 2022; Hegseth et al., 2021; Wayman, 2006). Few other works use a time analysis domain (Leimeister and Kolios, 2021; Leimeister et al., 2021; Gilloteaux and Bozonnet, 2014; Ferri et al., 2022; Ferri and Marino, 2022; Lemmer et al., 2020). Some work included a time domain to verify the work carried out in the frequency domain Karimi et al. (2017), Myhr and Nygaard (2012), Hegseth et al. (2020, 2021).

The effectiveness of an optimisation framework, and subsequent results, is dependent on the types of software available which are fit for purpose. Fig. 10 highlights how dependent this research is on both WAMIT and FAST for hydrodynamic and aerodynamic analysis. For this reason, a large number of the existing literature use non-gradient-based methods for their optimisation. However, authors such as Hegseth et al. (2020) use gradient-based optimisations, since they use formulae from which gradients can be derived.

In the work by Karimi et al. (2017) the hydrodynamic properties of the platform was found using WAMIT[1] which can then be combined with the equations of motions. Authors of Clauss and Birk (1996), Hall et al. (2013), Sclavounos et al. (2008), Birk and Clauss (2008) and Wayman (2006) followed a similar approach for hydrodynamic analysis. Hall et al. (2014) unlike Clauss and Birk (1996), Hall et al. (2013), Karimi et al. (2017) and Sclavounos et al. (2008) do not use WAMIT to find the hydrodynamic properties of each platform geometry; instead, WAMIT is used to find the hydrodynamic properties of six base designs, which can then be used as a starting point for optimisation. Fylling and Berthelsen (2011) use WAMOF3 rather than WAMIT to obtain the hydrodynamic coefficients and from these the motion transfer functions. A different technique was proposed in Hegseth et al. (2020, 2021): rather than using a potential flow code (e.g. WAMIT), they adopt the MacCamy-Fuchs theory to determine hydrodynamic excitation loads, while the added mass was based on analytical 2D coefficients, the Radiation damping was neglected, viscous damping was computed using a stochastic linearisation of the drag term in Morison's equation. Since this is a linear model, a time domain verification was carried out using SIMA.[2]

Gilloteaux and Bozonnet (2014) utilise DIODORE[3] software to find the hydrodynamic properties using the frequency domain, DeepLines[4] is then used to model the platform and mooring lines in the environment in the time domain.

Both Dou et al. (2020) and Pollini et al. (2021) use the Quick Load Analysis of floating offshore wind turbines model (QuLaF) to determine

[1] https://www.wamit.com/.
[2] https://www.sintef.no/en/software/sima/.
[3] https://www.principia-group.com/blog/product/diodore/.
[4] https://www.principia-group.com/blog/product/produit-deeplines/.

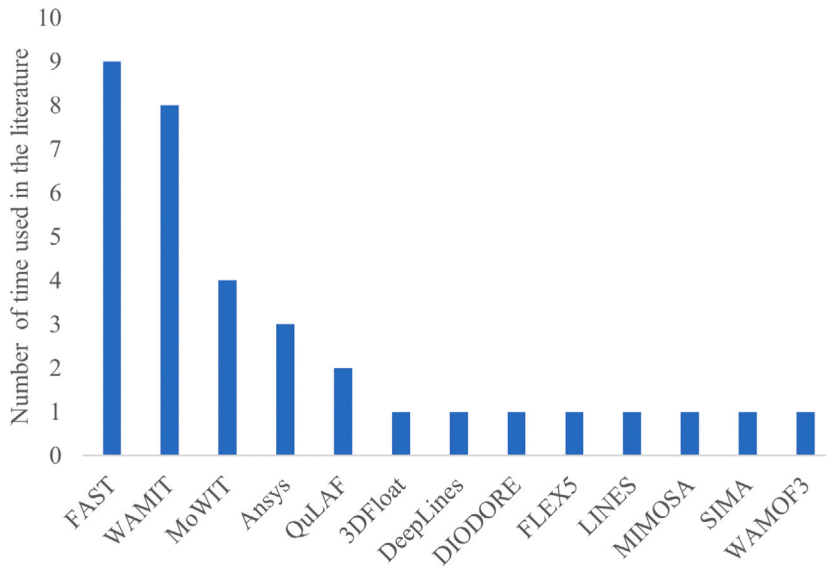

Fig. 10. Additional software used within the optimisation frameworks.

the hydrodynamics of the platform, a model created by Pegalajar-Jurado et al. (2018). The only works which use ANSYS AQWA to find the hydrodynamic forces were (Ferri et al., 2022; Ferri and Marino, 2022; Lemmer et al., 2020), this model was also verified with WAMIT in Ferri et al. (2022).

Bracco and Oberti (2022) apply an in-house hydrostatic tool, Ghigo et al. (2020) and Lemmer et al. (2020) also use basic hydrostatic concepts to determine the stability of the platforms.

Several authors (Karimi et al., 2017; Hall et al., 2013, 2014; Sclavounos et al., 2008; Dou et al., 2020; Pollini et al., 2021; Ferri et al., 2022; Wayman, 2006; Ferri and Marino, 2022) use FAST, this allows the influence of the rotor aerodynamics and the wind turbine mass effect on the FOWT motions to be considered. It can be noted that some of the aerodynamic effects on platform motion cans also be considered by utilising a frequency domain approach without using FAST. Karimi et al. (2017) utilise FAST as verification in the time domain, which shows the variation in the surge, pitch, and nacelle acceleration of a TLP and a SPAR. Lemmer et al. (2020) applied a similar approach and used FAST as a verification tool for their Simplified Low Other Wind Turbine Model (SLOW) methodology.

In work by Karimi et al. (2017) and Hall et al. (2013, 2014) the mooring lines are modelled using a quasi-static mooring subroutine of FAST. Fylling and Berthelsen (2011) use MIMOSA to perform extreme conditions for fatigue analysis on the mooring lines. Finally, Sclavounos et al. (2008) utilise the LINES software to find the properties of the mooring system. Hegseth et al. (2020) utilise a dynamic frequency-domain model to find the tension in the line, considering it only has one Degree of Freedom (DOF) (Larsen and Sandvik, 1990)

Research carried out by Leimeister and Kolios (2021), Leimeister et al. (2021, 2019) use MoWiT (Modelica library for Wind Turbines) to perform aero-hydro-servo-elastic analysis for the wind turbine, in the time domain. Similarly, Myhr and Nygaard (2012) also apply an aero-hydro-servo-elastic tool called 3DFLOAT and Hegseth et al. (2020, 2021) combines structural and control parts to create a full aero-hydro-servo-elastic model.

Bracco and Oberti (2022) did not include any dynamic modelling and focused purely on the hydrostatics of the platform to assess the stability. Benifla and Adam (2022) also do not include any dynamic modelling; however, it does use Ansys SOLID186 to perform finite element analysis and FLEX5 to determine the loading on the platform.

3.8. Cost models

Cost is one of, if not the, most important and utilised objective within this area. For papers which do not include cost as the main objective, the cost can often be linked to the objective implemented. Therefore, the following section is dedicated to this important objective. Table 2 provides a systematic analysis of the cost aspects considered in each reference cited.

The section is broken down as follows: Section 3.8.1, highlights the simplistic models used within literature, and Section 3.8.2 details the more complex cost models used. The mooring line cost models are presented in Section 3.8.3, which is followed by other costs considered in Section 3.8.4. Finally, Section 3.8.5 details objectives which have been used and can be linked indirectly to the costs.

3.8.1. Reduced complexity model

Karimi et al. (2017) and Hall et al. (2013) use the same cost model, including the support structure and mooring lines. The cost of the platform is found using the mass of the platform combined with the cost per unit of mass. It is stated in both works that this includes material cost, manufacturing, and installation considerations. Bracco and Oberti (2022) determine the cost of the platform in a similar manner to Karimi et al. (2017) and Hall et al. (2013), i.e. using a simplistic "bill of material" approach, similar to a number of other papers (Ghigo et al., 2020; Myhr and Nygaard, 2012; Sclavounos et al., 2008; Benifla and Adam, 2022; Lemmer et al., 2020). Additional considerations were added in Wayman (2006), by expressing the material cost in GBP/kg and the labour cost, expressed in GBP/hour. To determine the cost, Fylling and Berthelsen (2011) use a different approach starting with the initial price for the SPAR, which was then scaled in proportion to the dimensions of the new optimised SPAR.

From this review, it was made very clear that the most common method to find the platform cost was to consider the mass of the platform and multiply it by a value for the price of material per kg. One of the best cost models found within the optimisation literature was presented in Ferri and Marino (2022). This model considers not only the platform mass, but the associated labour costs for welding and assembly, in terms of hours and the paint cost in correspondence with the surface area covered. The ballast to meet the required draft is also found and the cost of ballast made in concrete is calculated.

Table 2
Summary of the reviewed works in Section 3.8, describing the support structure, tower structure, mooring line, anchor, cable, AEP, additional costs, optimisation related costs, LCoE, and relevant notes.

Ref.	Support structure	Tower structure	Mooring line	Anchor	Cable	AEP	Additional costs	Optimisation related costs	LCoE	Notes
Hegseth et al. (2020)	Mass times steel cost factor plus the fabrication factor multiplied by time, considering: material assembly, welding, and painting costs (2.7 EUR/kg).	Same as support structure	Uses mass (3.5 EUR/kg)	X	X	X	Cost and standard deviation of the rotor were combined, with weighted factors, then used in optimisation process	Support structure, tower, mooring and rotor standard deviation	X	Aim to minimise standard deviation of rotor speed
Hall et al. (2013), and Karimi et al. (2017)	Mass of platform, including fabrication and installation considerations (2.5 USD/kg).	X	Total length and maximum steady state tension (0.42 USD/m-kN)	Anchor cost is a function of the maximum steady-state load, the installation cost is also included. 100–150 USD/anchor kN and 5000–11 000 USD/anchor installation	X	X	X	Support structure and mooring lines	X	X
Hall et al. (2014)	X	X	X	X	X	X	X	X	X	Minimising nacelle acceleration, which would reduce fatigue and hence maintenance costs
Leimeister and Kolios (2021)	X	X	X	X	X	X	X	X	X	Minimise nacelle acceleration and total inclination angle
Clauss and Birk (1996) (O&G)	X	X	X	X	X	X	X	X	X	Minimise platform forces and motions
Wayman (2006)	Mass of platform and labour costs (USD/ton and 40 USD/h).	X	X	Mooring line, anchor and two installation cost options: Barge, tug, labour, pumps and divers, anchor handling vessel. \$25 000–\$50 000 per anchor, installation 11 285.71–18 000 USD/per anchor	X	Uses Weibull and power curve of wind turbine	Installation cost port: hours and workers per installation, labour rate and crane fee. Installation cost at sea: installations per day, labour, crane, barge, tug hire. Total installation = \$145 280 per turbine	Cost is not included in optimisation	Does not include a discount rate, or the full cost of the system	Aim is to achieve restoring (increased stability)
Sandner et al. (2014)	X	X	X	X	X	X	X	X	X	Aim too minimises deviations in rotor speed and platform dynamics
Leimeister et al. (2019)	X	X	X	X	X	X	X	X	X	Aim too minimise nacelle acceleration, translational motion and total inclination angle
Pollini et al. (2021)	Mass only	X	X	X	X	X	X	Support structure	X	X
Gilloteaux and Bozonnet (2014)	X	X	X	X	X	X	X	X	X	Aim is to ensure floating structures maintain stability
Birk and Clauss (2008)	X	X	X	X	X	X	X	X	X	Aim too minimise significant heave double amplitude
Ghigo et al. (2020)	Platform mass, the steel density is increased to consider flanges and welds (3000 EUR/ton)	X	Fixed value (£500 Million)	Fixed value (£80 000)	X	Used historical data to get Weibull distribution, then multiplied by the turbines power curve	X	Only mass used for optimisation	Array cables 400 EUR/m, export cables 600 EUR/m, offshore and onshore substation 0.431 millionEUR, cable duct 500 EUR/m, installation (2.5 and 1.5 million EUR/MW SPAR and Hexafloat respectively), Decommissioning 2% and O&M 0.91 MNOK/MW	Uses discount rate, and includes all costs
Leimeister et al. (2021)	X	X	X	X	X	X	X	X	X	Aim too minimise the variation in power output
Leimeister et al. (2020)	X	X	X	X	X	X	X	X	X	Aim too minimise nacelle acceleration, translational motion and total inclination angle
Sclavounos et al. (2008)	X	X	X	X	X	X	X	X	X	Aim too minimise nacelle acceleration

(continued on next page)

Table 2 (*continued*).

Ref.	Support structure	Tower structure	Mooring line	Anchor	Cable	AEP	Additional costs	Optimisation related costs	LCoE	Notes
Fylling and Berthelsen (2011)	Uses and initial cost of a SPAR and scales it depending on the SPAR dimension (diameter, length and depth), the platform is considered in sections	X	Cost per unit of mass, length and mass of each segment	X	Cost per unit bare cable per unit length, cost of buoyancy material per unit mass, density and cross sectional area of material, length of each cable segment	X	X	Support structure and mooring lines	X	X
Myhr and Nygaard (2012)	Only Mass	X	X	X	X	X	X	Support structure	X	X
Hegseth et al. (2021)	Mass times steel cost factor plus the fabrication factor multiplied by time, considering: material assembly, welding and painting costs (2.7 EUR/kg)	Same as support structure	X	X	X	X	X	Support structure and tower	X	X
Ferri et al. (2022)	X	X	X	X	X	X	X	X	X	Aim to minimise surge, heave, pitch RAO amplitudes
Bracco and Oberti (2022)	Material cost times mass (3000 EUR/ton)	X	X	X	X	X	X	Support structure	X	X
Benifla and Adam (2022), and Lemmer et al. (2020)	Material cost times mass	X	X	X	X	X	X	Support structure	X	X
Ferri and Marino (2022)	Material cost (0.5 EUR/kg), ballast material(0.1 EUR/kg), labour(17.05 EUR/h) and paint cost(12.5 EUR/m^2)	X	Mooring line (1.6–2 EUR/kg)	Anchor cost(6706–10 250 EUR/kg)	X	Weibull and turbine power curve	X	Support structure and mooring line	X	X

3.8.2. Improved model

Hegseth et al. (2020, 2021) recognise that only considering the mass could lead to an underestimation of the costs, as it does not include any other manufacturing costs. For this reason, they model the tower and SPAR costs by considering the material cost and the fabrication costs, which include forming, assembly, welding, and painting by using a fabrication constant which is multiplied by the length of time to manufacture the product. No other details have been provided about this work.

Zhou et al. (2021) carried out a sensitivity study to determine which parameters effects the cost most for a semi-submersible. For this work, a detailed cost model was used to determine material, forming, welding and painting using the method found in Farkas and Jármai (2013). There was however no structural consideration for stiffeners of the required thickness of the shell. Zhou et al. (2021) found the radius of the columns had the largest effect on the overall cost.

3.8.3. Mooring line cost

As far as the mooring system costs are concerned, Fylling and Berthelsen (2011) found the cost of the mooring line by simply multiplying the mass per unit length, the length, and the cost per unit mass. A more advanced method was considered in Karimi et al. (2017) and Hall et al. (2013): by finding the cost based on the length of the mooring line and the maximum steady-state tension, considerations for the possible requirement for a thicker line are allowed. Similarly, the anchorage cost is a combination of a fixed installation cost and the anchor itself, which can be derived by multiplying a coefficient of cost per unit load by the maximum steady-state load on the anchor. The coefficient depends on which of the three main anchor types is considered (Karimi et al., 2017; Hall et al., 2013). The mooring line cost, unlike in other works, is calculated based on the mass of the line in Hegseth et al. (2020). Ferri and Marino (2022) is the only research to show how the anchor size is calculated using ABS anchor design document (ABS, 2022), once the required weight was found considering an ultimate holding capacity of 1.5 times the maximum mooring line tension from the weight, the cost can be then found. The mooring line cost considers the diameter required and the unstretched length. The unstretched length was found using the quasi-static approach presented in Hegseth et al. (2020). In later work by Hegseth et al. (2021), the cost of the mooring was discarded and the focus was solely on the tower and support structure. Anchor and mooring costs were derived considering, respectively, a fixed value and a cost per unit length. Wayman (2006) also consider the installation cost, based on the time to carry out the installation and the cost to hire the related vessels. From all of the optimisation papers reviewed, 18.5% considered the cost of the mooring line within their optimisation.

3.8.4. Other costs

Fylling and Berthelsen (2011) were the only group to consider the cost of the power cable. The power cable cost is related to the cost per unit length of the bare cable, the cost of the buoyancy material per unit mass, the density and the cross-section of the buoyant material, and the length of the power cable segments. The buoyancy material or its purpose is not explicitly stated in this work, however, it is expected to be an elongated segment(s) of buoyant material around the cable used to keep a required length of cable buoyant underwater, reducing the tension at the connection to the wind turbine (Subsea, 2023; Deep Water Buoyancy, 2022). Anchor, mooring line, and installation costs are briefly discussed in Bracco and Oberti (2022), but are not considered in the optimisation. Other authors that also included additional costs outwith the optimisation are (Ghigo et al., 2020; Wayman, 2006).

An important additional parameter that can be evaluated by knowing the total cost is the Levelised Cost of Energy (LCoE), if a model to quantify the annual energy production (AEP) is available. Both Ghigo et al. (2020), Wayman (2006) and Ferri and Marino (2022) use a simple method to find the AEP, by combining a Weibull distribution with the wind turbine power curve, which provides the electric power produced as a function of the wind speed. When finding the LCoE, both authors (Ghigo et al., 2020; Wayman, 2006) combined the summation of cost and divided it by the AEP, however Wayman (2006) lacks the inclusion of all associated costs and does not include a discount rate, which is important given the expected life span of around 25 years. The costs neglected were parts of the CAPEX related to the complete turbine and electrical system costs, operations and maintenance costs, and decommissioning costs. On the other hand (Ghigo et al., 2020) estimate the remaining cost using the following assumptions: cost per MW for the complete wind turbine, operations and maintenance, installation cost, and a set value for mooring lines, anchors, offshore and onshore substation, decommissioning, and cost per unit length for electrical cables and cable ducts. Ghigo et al. (2020) include a more detailed cost estimate compared to Wayman (2006), however, a number of assumptions are made in this work, and the accuracy of these are unknown since there is little data to validate such assumptions. Ghigo et al. (2020) also assume a fixed installation cost, which is inaccurate considering that it is heavily related to the type of platform, the site, and the installation techniques used. The operation and maintenance cost was considered as a cost per MW value, however, this is a far more complex problem since it is related to weather windows, failure rates, mobilisation, and downtime, which are key factors affecting the wind farms energy production. These parameters affecting the O&M cost are highly dependant on the site and the platform, hence a generic approach is not accurate. Decommissioning is a relatively new topic, with only a few bottom-fixed offshore wind farms now coming to the end of their operational life, Ghigo et al. (2020) assume decommissioning cost to be 2% of the CAPEX. Similar to other costs related to floating offshore wind, DECEX will also be affected by the platform type and cannot be standardised. Other fixed cost, such as mooring and anchors, were expressed as generic values for all platform types (Ghigo et al., 2020): these are in general not the same for all platforms, and depend on sites too. Different platforms require different mooring arrangements and anchors, depending on the seabed. The length of the mooring lines will also vary depending on the depth of the water, affecting the cost associated with the mooring lines. Similar to the work in Ghigo et al. (2020), Sclavounos et al. (2008) find the optimal platforms first using only the platform cost which is then followed by an economic assessment, based on cost per kW values with no breakdown of the cost values included.

3.8.5. Indirect cost model

The following papers (Hall et al., 2014; Leimeister and Kolios, 2021; Clauss and Birk, 1996; Sandner et al., 2014; Leimeister et al., 2019; Gilloteaux and Bozonnet, 2014; Birk and Clauss, 2008; Leimeister et al., 2020; Sclavounos et al., 2008; Ferri et al., 2022) do not explicitly include a cost model, but, in their optimisation framework, the objective function can be very easily related to cost. Hall et al. (2014), Leimeister and Kolios (2021) and Sclavounos et al. (2008) has as objective the (minimisation of) the nacelle acceleration, which in turn should reduce fatigue and maintenance costs. A reduction in the platform motion, in general, should improve the power output from the turbine, augmenting the AEP and therefore driving down the LCoE. Another benefit of reducing platform motions is the reduction in ultimate and fatigue loads, overall improving the life span and reducing maintenance costs. The objective of reducing the angle of inclination of the tower would also help to improve power performance and hence the LCoE (Leimeister and Kolios, 2021; Leimeister et al., 2019, 2020) Similar effects would arise from reducing the forces or motions of the platform (Birk and Clauss, 2008; Clauss and Birk, 1996; Sandner et al., 2014; Ferri et al., 2022).

For the sake of completeness, the review's summary is also reported in Table 2, where **X** highlights that this system is excluded from the research.

4. Discussion and future work

The following section is broken into three parts, firstly, a discussion on the optimisation frameworks in the literature is reported in Section 4.1. This section is then further broken down into design variables, objectives, and constraints. Then a review of the overall output of each paper is provided in Section 4.2, followed by potential future work to help improve the area of research in Section 4.3.

4.1. Optimisation framework

Firstly, focusing on the optimisation frameworks found in the literature, the percentage of each system (i.e floater, mooring, tower etc.) to which design variables, objectives and constraints are applied can be found in Table 3.

4.1.1. Design variables

Starting with design variables, roughly 93% of the literature uses design variables to describe the floater—this is expected since the main focus of the present work is on optimisation of floating substructures. In comparison, the next most represented system in the design variable vector is the mooring system, again as expected, although only half of the reviewed literature have included it. The control, cable, and tower systems were rarely included, and no system/subsystem belonging to the Rotor Nacelle Assembly (RNA) has been included. It is expected that these inclusions will help to find, overall a better platform, considering the complex and interconnected relationships between systems.

4.1.2. Objectives

The majority of literature (83%) has cost as objective of the optimisation, while 58% of them consider the dynamic response of the platform as one of the objectives. Clearly, 83% and 58% come to a total greater than 100%, the reason for this is the fact that the following works considered multi-objective functions: Hall et al. (2013, 2014), Karimi et al. (2017), Leimeister et al. (2021), Wayman (2006), Birk and Clauss (2008), Ghigo et al. (2020), Leimeister and Kolios (2021), Leimeister et al. (2020), Pillai et al. (2018) and Ferri and Marino (2022). The mooring system is included in approximately 11% of the objective functions, by Myhr and Nygaard (2012) and Sclavounos et al. (2008). The mooring line has very few appearances in the objective function but the majority of the research have considerations for it (Karimi et al., 2017; Sclavounos et al., 2008; Leimeister et al., 2020; Fylling and Berthelsen, 2011; Hall et al., 2013; Ferri and Marino, 2022; Hall et al., 2014; Gilloteaux and Bozonnet, 2014; Myhr and Nygaard, 2012; Dou et al., 2020; Hegseth et al., 2020; Zhou et al., 2021; Hegseth et al., 2021; Pollini et al., 2021; Pillai et al., 2018; Sandner et al., 2014; Leimeister et al., 2021; Ferri et al., 2022;). A possible reason is the expected percentage of the cost. The mooring line is predicted to be between 1% to 6.5% of the overall cost depending on platform type (Maienza et al., 2020). Since the cost of the various floating substructures excluding the mooring cost, lies between 20% and 27% there is a potential to make a much more significant impact on the overall cost reduction (Maienza et al., 2020). The mooring line might be better considered in the optimisation as a constraint, to ensure the tension remains below the minimum breaking load. By considering the mooring line in this sense the minimum diameter and length can be found, giving a cheaper design while still considering a safety factor. The tower and the power production are both considered in the objective function in roughly 7% of research. Given that wind turbine towers have been in production and operation for a much longer period of time compared to the support structure, it makes sense for an optimal design to already be known, removing the requirement for the tower to be part of the objective function. However, when considering structural considerations and eigen frequencies, it could be relevant to consider the tower in the optimisation, since floating wind turbines have a dynamic response to the metocean conditions substantially different from onshore and offshore fixed wind turbines. The consideration of the power produced is relatively low considering that the more energy is produced the higher the revenue, and this is potentially due to only very few works (Hegseth et al., 2020, 2021; Sandner et al., 2014) considering the controller, which is associated with improving power output. The power production, similarly to cost, can be improved by improving the platform's response, and hence geometry and mooring system. As mentioned an improved control system would also have a positive impact on the power production. Increased power production will push down the LCoE making offshore wind more competitive. Overall, it is clear that all systems are highly interconnected, with a strong correlation to cost.

Table 3
Percentage of the literature reviewed considering a specific floating wind turbine subsystem or aspect in the design variables, objectives, and constraints.

	Control	RNA	Tower	Floater	Mooring	Cable	Power	Cost	Resp.
Design variables	10.71%	0.00%	14.29%	92.86%	50.00%	3.57%	0.00%	0.00%	0.00%
Design objectives	0.00%	0.00%	7.14%	0.00%	10.71%	0.00%	7.14%	82.14%	57.14%
Design constraints	7.14%	3.57%	17.86%	78.57%	50.00%	10.71%	3.57%	17.86%	92.86%

4.1.3. Constraints

In terms of design constraints, the most common (92.86%) are related to the platform dynamic response, which includes nacelle acceleration, platform motion, and natural frequencies, all of which are expressed in more detail in Section 3.4. Furthermore, constraints are commonly imposed on the platform geometry (78.57%) to ensure feasibility/manufacturability/transportability are considered within the optimisation. Constraining the design variables also reduces the design space to help improve computational time. Mooring line constraints are applied in 50% of current research, more specifically imposing limits on the maximum tension in the mooring line. Applying constraints which reflect maximum values like that of the mooring line tension is a good way to consider design standards, which eventually each substructure will have to comply with. Both cost and tower constraints are represented in 17.86% of research, the latter makes sense since the tower is required to be a certain geometry with the hub height being an important constraint. A cost constraint, however, as expressed in Section 3.4 is not expected to be related to finding the best platform but to remove economically unfeasible designs and reduce the design space and therefore computational time. Since the control, RNA, cable and power production are rarely seen in the literature, they are uncommon in the design constraints applied to the optimisation.

4.2. Literature findings

A number of articles have performed multiple platform optimisation ranked the platforms from best to worst, see Table 6. It can very quickly be noticed there is no clear consensus on which platform is 'best'. Most of these platforms are ranked on the basis of cost, and nearly all of them use slightly different cost models and different site characteristics. The use of cost per unit of mass could easily cause bias in ranking which platform is best, not considering the complexity, manufacturability, transportation, installation, operations and maintenance, and lastly decommissioning. Similarly, the different sites explored by each paper will have a direct impact on cost, further afield and deeper sites are expected to be more expensive making it difficult to compare them directly.

4.2.1. Tension leg platform

Karimi et al. (2017) found that the TLP is the optimum solution, while the multibody platform optimisation found a semi-submersible with four columns to be the most cost-effective, yet stable platform. Both Karimi et al. (2017) and Hall et al. (2013) conducted similar work producing similar results. Their results are presented on graphs with nacelle acceleration vs. cost, showing the Pareto frontier, making it very easy to observe the best performing platforms for these optimisations. Similarly, Hall et al. (2014) and Sclavounos et al. (2008) also find that a TLP is optimal with a semi-submersible also considered a strong platform choice for the given objective in Hall et al. (2014). The TLP in Sclavounos et al. (2008) is expected to be the best solution due to its low nacelle accelerations and mass. Similarly, the outcome of Wayman (2006) shows the SPAR to be the most expensive and a barge—the cheapest, followed very closely by a TLP. It has been noted that at no point was a SPAR the optimal solution (Hall et al., 2013, 2014; Karimi et al., 2017; Sclavounos et al., 2008; Wayman, 2006). In these studies, however, the manufacturing complexity, which is generally higher for column-stabilised platforms, and its impact on the costs derived, is not taken into account. Taking this aspect into account may have favoured the SPAR, thanks to its simpler geometry. The complexity factor of manufacturing for each specific platform was considered in the work by Bracco and Oberti (2022), see Table 4. Since the work in Bracco and Oberti (2022) is for existing prototypes, it is wondered how universal a complexity factor is when considering a design space with non-existent platform types. Since there is a wide range of very different, for example, semi-submersible platform geometries, the complexity factor is expected to vary. Both the optimisation and cost literaturereference myself which presents a complexity factor consideration is always fixed to one value for the three main platform classifications.

Table 4
Complexity factors used in Bracco and Oberti (2022).

Platform type	Complexity factor
Hwyind SPAR	120%
PelaStar TLP	150%
Wind star TLP	170%
WindFloat Semi-submersible	200%

Similar to Karimi et al. (2017), Hall et al. (2013), Sclavounos et al. (2008) and Hall et al. (2014), Bracco and Oberti (2022) use the same method as Ghigo et al. (2020) and the outcome of each paper is that the TLP is the cheapest option, however, there is no consideration of which platform has the best trade-off between cost and stability, unlike work in Karimi et al. (2017), Hall et al. (2013) and Sclavounos et al. (2008). Only considering the lowest platform cost has the potential to find not only an infeasible solution in terms of performance but also a platform that may not guarantee the lowest overall cost. The works described above all find the TLP as the best option with the main reasons being linked to potentially good performance and low cost. Since a TLP has been repeatedly presented as the most optimal option, there has been additional work done to explore non-traditional TLP geometries. Myhr and Nygaard (2012) highlight the traditional TLB without the space frame performs best, with the TLB with a space frame giving very similar results. This work highlights the negative impact on moving away from traditional TLBs by implementing a space-frame. Benifla and Adam (2022) compare the standard TLP buoy with the UBB and then the optimised UBB. Both UBB platforms have a higher mass, however, also a lower cost with the optimised UBB having a 30% cost reduction. The above works show a low cost with potential for large cost reduction, making the TLP a favourable option. Since the manufacturability is not fully represented in this work, comparing welding, forming, and paint costs might alter which platform is cheapest. Additionally, when considering the full picture, it is expected that the capital cost and installation cost of the station keeping system for a TLP will be much larger than the SPAR and semi-submersible due to its higher complexity (Myhr et al., 2014; Bjerkseter and Ågotnes, 2013; Heidari, 2017) see Fig. 11.

Since the mooring, installation, operation, maintenance, and the decommissioning cost for each platform type is different, the cheapest platform option might not be the overall cheapest design when considering the life span of the platform. Considering the LCoE found in cost model research, it can be identified that the cost and cheapest platform vary from site to site, see Table 5. It is notable that since each model and the assumptions made in each differ the LCoE will be effected by this.

Due to the reasons highlighted above, a proposed approach would be to optimise the appropriate platforms for a given site, finding the best platform based on cost and performance. Work by Clauss and Birk

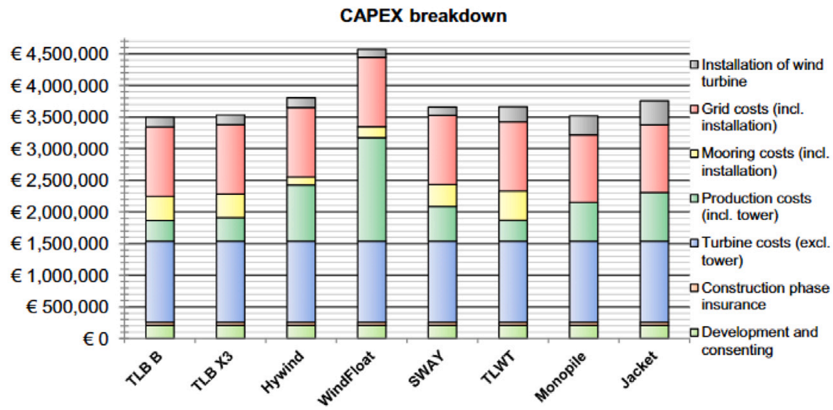

Fig. 11. Cost breakdown found in Myhr et al. (2014).

Table 5
LCoE found in cost model literature.

Reference	SPAR [Euro/MWh]	Semi-submersible [Euro/MWh]	TLP [Euro/MWh]	Water depth [m]	Distance to shore [km]	Farm power [MW]
Lerch et al. (2018)	82	78	N/A	70	38	500
Lerch et al. (2018)	93	93	83	130	57.8	500
Lerch et al. (2018)	120	112	108	100	180	500
Maienza et al. (2020)	94.17	91.97	106.7	135	16	125
Heidari (2017)	137.8	147.8	141.8	100	50	490
Stehly et al. (2020)	N/A	132	N/A	36	16	600
Castro-Santos et al. (2020a)	184.52	172.81	187.98	N/A	N/A	106.575
Castro-Santos et al. (2020b)	289.49	303.97	325.6	N/A	N/A	106.575
Castro-Santos et al. (2016)	N/A	415	N/A	90	25.5	106.57
Castro-Santos et al. (2016)	N/A	442	N/A	90	43.6	106.57
Martinez and Iglesias (2022)	N/A	135	N/A	200	350	1000
Myhr et al. (2014), and Bjerkseter and Ågotnes (2013)	133.55	157.2	120.4	200	200	5000
Judge et al. (2019)	161	161	161	N/A	30	30

(1996) focuses on a range of O&G platforms, which considers the notion of finding the best geometry for each platform type. It was shown that the downtime of a semi-submersible can be reduced from 15.5% to 2.5% and the sub-submersible once optimised has a decrease in 70% of vertical excitation forces due to changes in shape. The maximum cyclic tendon force is reduced by 40% for the TLP and, finally, the gravity-based structure once optimised has a decreased overturning moment by 78%. Since this work finds the optimal platform geometry for each substructure type, its cost can then be combined with a complete LCoE model which can provide even more insight into which platform is best in a monetary sense, considering the energy produced. Bracco and Oberti (2022) also propose the inclusion of energy performance and a more detailed cost model for each platform in future work, which takes into account manufacturing costs, as well as other related costs.

4.2.2. Semi-submersible

The semi-submersible has been highlighted as a good option in Hall et al. (2013, 2014), Karimi et al. (2017), Lemmer et al. (2020), Ferri et al. (2022) and Ferri and Marino (2022). It has been observed that by adding heave plates, a greater reduction in the acceleration of the nacelle can be observed than by increasing the radius of the platform (Karimi et al., 2017). This could be a cheaper alternative to achieve the desired response at a lower cost without making the platform larger. Drawing a comparison between platforms which are characterised by the same nacelle acceleration with and without heave plates could also provide useful insight. This consideration could, potentially, make the semi-submersible competitive against the low cost TLP described in previous works. Lemmer et al. (2020) focus on optimising semi-submersibles with heave plates and it was found that the platform with the shallowest draft provides the lowest nacelle acceleration and is the best at reject disturbances. Ferri and Marino (2022) found that for both sites analyses the general trend is for increased overall radius, and narrow, intermediate draft columns, to obtain the best trade-off between cost and performance.

4.2.3. SPAR

The work carried out over the years by Leimeister et al. (2018, 2020, 2021) has had a primary focus on SPAR platforms, finding the optimised SPAR having a lot lower mass than the original un-optimised OC3 SPAR, which had a prior purpose of code-to-code comparison. In 2018, it was found that the optimised SPAR had 80% of the original floater steel mass, and around 44% less ballast (Leimeister et al., 2018). It was also found that the optimised SPAR had not only reduced mass but improved performance compared to the original design (Leimeister et al., 2020, 2021). Similarly, in 2019, Leimeister et al. (2019) proved that the 7.5 MW turbine would only require a slightly larger SPAR than that of the OC3 SPAR for the 5 MW turbine, again verifying the OC3 SPAR is over-engineered. Comparable to the work done by Leimeister et al. (2018, 2019, 2020, 2021), Leimeister and Kolios (2021), the optimised SPAR geometry in Fylling and Berthelsen (2011) also shows a maximum reduction of 23% in cost for extreme weather conditions. When fatigue constraints are added, the shape of the SPAR is similar, but slightly larger, but still 18% cheaper than the initial platform. The largest reduction in cost of a SPAR (33%) was found in the work by Dou et al. (2020) when considering static conditions and 24% when considering dynamics within the model. Unlike any other work on the optimisation of a SPAR, Pollini et al. (2021) finds the fully optimised platform to be more expensive than the initial design. Similar to work by Leimeister et al., Birk and Clauss (2008) only optimises the SPAR platform. The results give five different designs that are all optimal but perform better under different conditions. For example, one of the designs gives the smallest area under the RAO, whereas another has the

Table 6
Details of the platforms ranked in literature from best (left) to worst (right).

Reference	Best to worst			
Sclavounos et al. (2008)	SPAR	TLP	–	–
Bracco and Oberti (2022)	TLP	SPAR	Semi-submersible	–
Ghigo et al. (2020)	TLP	SPAR	–	–
Wayman (2006)	Barge	TLP	SPAR	Semi-submersible
Hall et al. (2013)	Semi-submersible	TLP	SPAR	–
Hall et al. (2014)	Semi-submersible	TLP	SPAR	–
Karimi et al. (2017)	Semi-submersible	TLP	SPAR	–

lowest draft. While both still meet the design constraints, the platform with the lower draft is expected to be cheaper in terms of CAPEX. The O&M cost, however, might be cheaper for the design with the smaller response, no work has been done to consider this. The expected reason for this is the CAPEX is predicted to lie between 60–70% of the overall cost and the OPEX is only 25–30%, pushing the focus on the CAPEX reduction (Maienza et al., 2020). The consideration of different conditions is key in determining the best platform. This is even more relevant when considering each site will have different conditions, changing which platform is best for the site.

Hegseth et al. (2020, 2021) produce an optimised SPAR shape similar to that of the work by Clauss and Birk (1996) presenting an hourglass shape below the waterline with the addition of a traditional tapered tower. In Hegseth et al. (2020) the thickness is considered to vary from SPAR to tower, showing that the SPAR requires thicker steel than the tower. Hegseth et al. (2020) highlight the controller design as highly important to normalise the rotor speed deviation, improving it by 10.9%. In 2021, Hegseth et al. (2021) found that by applying fatigue constraints, there was a constant reduction in fatigue damage of roughly 65% and an increase in the reliability index from 1.12 to 2.5. Overall, a cost reduction of 5–11% was presented in Hegseth et al. (2021), which is mainly due to improvements in the design of the platform driven by the buckling of the shell and hydrodynamic stability. This is one of the lower reductions found in this review, which is expected to be related to the consideration of structural constraints, ensuring the platform has the correct thickness of steel, which affects its cost. This is directly related to the material cost as well as the forming and welding cost. The lower expected reduction in capital cost presented in this work seems more realistic than 33%. The work by Hegseth et al. (2021) however does not predict the reduction in O&M cost which would expect a reduction since the reliability index increases, leading to a greater overall reduction in cost. A potential improvement in the work by Hegseth et al. (2020, 2021) would be to add an AEP model, resulting in a possibly improved outcome, since the controller is also optimised, improving the power output and reducing the LCoE.

Ferri et al. (2022) carry out multiple optimisations with an increasing number of design variables and resulting in different values for the platform variables. The platform shape also changes depending on whether it was optimised for surge, heave or pitch. This shows that it is important to consider all motions combined to get the best overall performance.

4.3. Future work

In the initial research by Wayman (2006), areas of suggested future work included: development of a fully integrated time domain analysis and modelling tool, detailed design, cost analysis, structural analysis, turbine control mitigation, active or passive inertial control of the platform for motion mitigation, and, finally, careful consideration of the design of a wind turbine suitable for offshore deployment. Since then, in the past 16 years, improvements have been made in the majority of the areas that were highlighted. There are, however, still areas which could be improved. The following paragraphs summarise potential improvements.

The majority of cost models reviewed only consider the cost per unit mass of the materials used, and, therefore, the optimisation is limited to a minimisation of the amount of material used. Typically, the unit value per mass used is higher than just the material (steel/concrete/ballast) cost, in order to include consideration for other costs such as welding, painting, forming and labour. These approaches adopt the hypothesis that all of the above additional listed costs are linearly proportional to the mass of the material considered. This may be violated, for example, when considering welding costs, since they are also related to the complexity of the structure, i.e. number of joints, the time to carry out the work, the labourer, and then any other overheads. The forming cost of the material is highly related to the thickness of the material, which in tow effects the difficult to roll the plates. When the forming process becomes to difficult it requires a greater number of plates rolled at a smaller angle, increasing the number of welds.

In some cases, it would be straightforward to develop a more advanced cost approach considering these factors. For example, in the work of Hegseth et al. (2020), the SPAR platform is split into ten segments. This create an opportunity to include the additional cost related to the joints between each segment. This could easily be expanded to include the cost to weld curved plates together to get the completed segment. The painting cost, rather than being related to the mass, is better described by the surface area covered, which could also include labouring, time and overhead costs. Plate forming is an important process to create the curved shells which make up the cylindrical segments. Since the scale of these parts is large, it would be done by large machinery, which would come at a cost, related to the time, labour, and overheads.

Generally, cost models use the same cost per kg value for all three platform typologies, which creates a bias based on the mass of the platforms. This is not fully justified since other factors such as forming, welding, and painting are included in the cost as well as the material cost. In fact, the simple SPAR design (essentially a cylinder) has often a larger mass than a TLP or Semi-submersible counterpart, but this methodology fails to acknowledge the SPARs ease of manufacturability—leading to an unfair comparison A TLP pr a semi-submersible configuration may be more complex from a manufacturing point of view, considering the large number of main structural elements and bracings. In some instances, the cost model addresses this aspect by adding an additional complexity factor, however, calculating the additional costs would be more accurate and should be relatively easy if the geometry is known.

Based on the authors' knowledge, it would be more effective to independently optimise the platform base on cost. The output would the be combined with and external cost model to determine the total cost of the turbine and its support system. Since there are only two papers which detail other costs after finding the optimal platform, it is very difficult to determine which platform is 'best' or, in other words, cheapest. By combining the optimised platform cost with a complete model including installation, operations and maintenance, and decommissioning, the cheapest platform for a given site could be more accurately identified.

The installation cost is often expressed in terms of mass, and this may lead to inaccuracies. In cost modelling literature, the installation is often expressed as a cost per MW value, however, as found in previous work by the author, this cost also depends on vessel hire, vessel speed, fuel cost, fuel consumption, distance to site, time to install, and other parameters not usually considered in the literature. Considering there are only three operational floating offshore sites around the world, having accurate estimates for total installation time is difficult. However, it is even more challenging to determine the accuracy of assuming a cost per MW value with such little available data to validate this assumption. The inclusion of the installation cost in the GBP/kg value seems irrelevant since, as explained, it is not only related to the geometry of the platform, and the installation technique would be different for each platform. The authors do, however, agree that if the platform is larger then there could potentially be the requirement for larger vessels and large space which need to be hired at the port to store the platform, relating these costs to the mass. Considering the size of the platform for transportation could also improve the optimisation by ruling out platforms that would not be able to be transported due to their large size. The time to complete installation will also depend on the type of platform, as the geometry and mooring arrangements are different.

A number of papers recognise the requirement for a more accurate cost model and highlight this as an important area of further research, for example in Hegseth et al. (2020), Hall et al. (2013), Benifla and Adam (2022) and Bracco and Oberti (2022). As mentioned in Section 3.8, not all optimisation frameworks include cost models, however, by improving the performance of the system, the over arching aim is to achieve a positive effect on the cost. A method to quantify the positive impact on cost would be an interesting addition to these pieces of work. For example, the improvement in terms of reliability derived in Leimeister and Kolios (2021) could be translated to decreased operation and maintenance costs, and potential life extension. Similarly, improving the dynamic response of the platform should improve the AEP, therefore reducing the LCoE. Only two of the papers included in this review consider the AEP, however, the impact of the platform's dynamic responses on the power production is neglected. Recent work by Amaral et al. (2022) has created an AEP model that can be used in the time or frequency domain, considering platform motions. This could be a potential addition to optimisation frameworks in finding the LCoE value.

An enhancement which could be included in future work would be the platform applicability for each site. For example, a semi-submersible might be the cheapest option, but it could be inappropriate for the sites characteristics, however, in these same conditions a SPAR might be better. Similarly, if the water depth is limited to around 100 m, the SPAR might not be the best option. Weighing up the different considerations of the site and introducing this into the determination of the best platform for a specific site would be highly valuable. Lerch et al. (2018) (Table 5) show that the cost of the wind farms does change for the three proposed sites, which is in line with the authors' views, and confirms the consideration of each platform's cost at each specific site would be important, rather than predicting which platform is better than another in generic terms.

Another key takeaway is that the majority of work focused on SPAR platforms, probably due to their simplicity and early deployment. There have been some studies (Bracco and Oberti, 2022; Sclavounos et al., 2008; Ghigo et al., 2020; Wayman, 2006; Clauss and Birk, 1996; ;Hall et al., 2013, 2014; Karimi et al., 2017) comparing the three platform typologies. The authors recognise that including all three platform geometries creates a large design space, which is computationally very expensive to explore. A potential solution could be the development of a "preliminary concept selection" process to determine which platform is most appropriate for a given site. The elimination of even one design option would still reduce the optimisation time by around a third.

An important finding in this review was the repeated use of the 5 MW NREL wind turbine. The 15ME IEA wind turbine was only used once for the SPAR geometry. Since there has been such a rapid expansion in the size of wind turbine technology, lessons from the optimisation of the 5 MW turbine can be used to expand all platform typologies to the 15 MW wind turbine. The scaling method used in Leimeister et al. (2019) to expand from 5 MW to 7.5 MW could be a useful addition to optimisation frameworks, allowing a range of different wind turbines to be used in one framework, improving its flexibility.

Similar to the suggestions of Wayman (2006) the author expects the future work within this area will produce well-rounded multi-disciplinary models considering cost, energy production, structural, statics and dynamics of the platform together to find the most optimal platform which has been tested in a number of different load cases for six degrees of freedom. To reduce the computational expense linked to the expansion of current models using a platform selection tool as a pre-filter step for each specific site should also be considered. A shift to 15 MW and greater turbines is indefinitely the future of this area of research.

Overall, the work described above highlights the huge potential of implementing optimisation techniques within the industry in order to explore a wide range of platform geometries. An overview of everything discussed in Section 3 can be seen in Table 7. It is clear from this review that optimisation is a very powerful tool which could be used to designers' advantages to explore a wide range of designs, quickly discarding unacceptable designs.

5. Conclusion

With the ever-growing demand for energy around the globe, it has become essential to de-carbonise the grid by exploring alternative energy sources. Fixed offshore wind has already proved feasible, now with a lot of nearshore sites utilised further afield sites are required to keep up with demand. This has created a gap in the market for floating offshore wind. Since there is a greater, more consistent resource further offshore it creates potential for more efficient, cost-effective solutions. However, with new technology comes inherent risk and cost. Focusing on key areas which could benefit from cost reduction, could seek out a more competitive energy source in floating offshore wind. Honing in on the areas where cost reductions can be made is the key. Since CAPEX makes up the majority of cost at 70% overall, it is a cost which would benefit from a reduction. The offshore turbines and the floating platforms are the highest contributors to CAPEX. The turbines have a high TRL, whereas the floating support structures are relatively novel with only three operational floating wind farms around the world. This highlights the platform as a key area for improvement and learning to reduce the cost.

This review has shown that an optimisation framework to find the most optimal platform could be a fundamental tool in exploring a wide design space to find the best solution since the industry lacks maturity. The reduction in cost related to the optimisation of the platform is hoped to make floating offshore wind more competitive with other energy sources and reduce reliance on finite energy sources.

The purpose of this work was to identify the understanding matured and the knowledge gaps yet to be addressed in the current literature on the area of optimisation of floating offshore wind turbine support platforms. By finding potential weaknesses in the current work it is hoped they can be improved to help find the cheapest platform for a given site, in the least computationally inexpensive way.

This review has highlighted that there has been relatively little amount of work done on the optimisation of floating offshore platforms. However, from the research carried out a signification amount focused on SPAR platform optimisation (48%), with several papers (32%) considering all three platform types, with a relatively simplified geometrical model. Focusing more work on the optimisation of floating offshore platforms with more detailed work on each individual platform is expected to find new competitive solutions in the future.

Although there is little literature in this area, one of the main findings from this review is there is no universal solution, the site

Table 7
Optimisation overview.

Ref.	Support structure	Wind turbine power (MW)	Systems considered	Optimisation tool	Domain analysis	Objectives	Constraints	Design variables	Software used
Hegseth et al. (2020)	SPAR	10	Platform, Tower, Mooring system and control system	Sparse Nonlinear OPTimizer, SNOPT	Frequency domain with time domain verification	Power quality and system cost	SPAR: Fatigue damage (FLS): Shell buckling, Panel ring buckling, Column buckling, limit states(ULS), extreme response. Tower: Fatigue damage (buckling stress). Mooring system: max mooring tension, only horizontal anchor tension. Control system: Closed-loop poles must have negative real parts (ensure stability)	SPAR: Section length, diameter, thickness, and T-ring stiffer: distance between stiffeners, thickness, and length of web and flange. Tower: Diameter and wall thickness. Mooring System: diameter, total line length, depth of fairlead below SWL and horizontal distance between anchor and fairlead. Control System: Proportional and integral gain	SIMA
Hall et al. (2013)	SPAR, Semi-submersible and TLP	5	Platform, mooring	Cumulative Multi-Niching Genetic Algorithm CMN GA	Frequency Domain	Minimise cost and root mean square nacelle accelerations	Minimum and maximum bounds on radii of cylinders, structural cost capped ($9 million), static pitch angle limited to 9 degrees, dynamic pitch angle limit 10 degrees, mooring line slackness variation cannot be greater than 3 times the steady state line tension	Platform: Inner cylinder draft, radius, top taper ratio, number of outer cylinders, outer cylinder radius array, radius, draft, and radius of the heave plate. Truss member radius based on critical buckling load. Mooring System: Number of lines, length, fairlead position, and type of mooring system (catenary or taut). Anchor depends on mooring system variables	WAMIT and FAST
Hall et al. (2014)	SPAR, Semi-submersible, Cylinder, Barge, Ring and sub.	5	Platform	fminsearch MATLAB	Frequency domain	Minimise root mean square nacelle accelerations	Hydrodynamic properties	Hydrostatic stiffness's and wave excitation coefficients (added mass, damping, stiffness, and wave excitation)	WAMIT and FAST
Karimi et al. (2017)	SPAR, Semi-submersible and TLP	5	Platform, Mooring and Wind Turbine	Multi-objective Genetic Algorithm	Frequency Domain and time Domain Verification	Minimise cost and maximise performance (stability and nacelle acceleration)	Minimum freeboard 5 m, minimum and maximum for each design variable, diameter is not less than tower base diameter, truss diameter based on critical buckling load, platform must be less the £9 million, nacelle acceleration limited to 1 m^2/s, maximum degree of steady-state pitch angle, and constraint of the anchor line.	Inner cylinder draft, the inner cylinder radius, the top tapper ratio of inner cylinder, number of outer cylinders, the radius of outer cylinder array, the outer cylinder draft, the outer cylinder radius,the outer cylinder heave plate radius, Xm which determines which mooring arrangement is used.	WAMIT and FAST
Leimeister and Kolios (2021)	SPAR	5	Support Structure	Non-dominated sorting genetic algorithm II from Platypus	Time domain	Increase reliability, avoid oversized design (reduce cost), horizontal nacelle acceleration, system inclination angle, and dynamic translational motion to be used in the objective function	Design variables bending stress at the base of the tower, tensional stress of the mooring line, nacelle acceleration, angle of inclination, and translational motion	SPAR base diameter, height, ballast density and height	MoWiT
Clauss and Birk (1996) (O&G)	SPAR, Semi-submersible and TLP	N/A	Support Structure	Nonlinear programming - Tangent search method	N/A	Minimise double amplitude of forces and motions	Design variable constraints and floating stability variable to determine platform type. Gravity Base: Radius vector for first and last point column, cross-sectional area and its shape, volume, centre of buoyancy.	TLP: Displacement distribution, cross-sectional area of the column and column spacing. Cassion Semi-submersible: Vertical location of the center of buoyancy, the water-plane area, the draft and the bottom area) Semi-submersible: displacement ratio , buoyancy distribution of pontoons, cross section area in the middle of pontoons, diameter of hemispheres at both ends of pontoons	WAMIT

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Table 7 (*continued*).

Wayman (2006)	SPAR, Semi-submersible and TLP	5	Support Structure	N/A		Surface area reduction (reduce cost)	Draft constraints, sufficient restoring coefficient (in pitch) and TLP mooring line restoring	SPAR and Barge: Radius and height structure and ballast height. Additional terms of Trifloater: Number of cylinders, radius from origin to outer columns, height and radius of outer columns	WAMIT and FAST
Sandner et al. (2014)	SPAR	5	Support Structure			Maximise power		Support structure radius and draft	
Leimeister et al. (2019)	SPAR	7.5	Support Structure	Non-dominated sorting genetic algorithm II	Time domain	Minimise inclination angle, translational motion and horizontal nacelle acceleration	Design variables bounded, ballast height cannot exceed bottom cylinder height, bounds on the angle of inclination, translational motion, and acceleration of the nacelle	Bottom cylinder diameter and height, ballast density	MoWiT
Pollini et al. (2021)	SPAR	15	Support structure and mooring system	Sequential Quadratic Programming and relaxation induced neighbourhood search	Frequency Domain	Minimise cost of substructure and mooring system in terms of mass	Pitch motion, nacelle acceleration and pitch angle, static pitch and surge, design variable constraints (ensure non deformed shape) - buoyancy centre, mooring line length, vertical force fairlead and SPAR body/head diameters and natural frequencies	Length of main cylinder, diameter of SPAR body and head, depth of the fairlead, anchor radius and mooring line length	FAST, QuLAF
Gilloteaux and Bozonnet (2014)	Cylindrical body	5	Support structure (heave plates)	N/A	Frequency and Time domain	Maintain stability	Floater radius and draft, heave plate span, metacentric height, maximal tilt angle, maximum pitch angle, maximum acceleration of nacelle		DIODORE, DeepLines
Birk and Clauss (2008)	SPAR		Support structure	Multi-objective Evolutionary Algorithm, ϵ-MOEA	Frequency Domain	Minimise double amplitude of heave motion, heave resonance and draft (cost and location consideration)	Design variable constraints, minimum metacentric height, heave response and maximum diameter of cylinder	3 sections: 3 area ratios, length ratios and lengths and draft	WAMIT
Ghigo et al. (2020)	SPAR, Semi-submersible and TLP (5 platforms)	5 and 10	Support structure	Genetic Algorithm		Minimise weight (cost) but ensure buoyancy and static stability	Minimum draft, Metacentric height, freeboard and maximum static pitch angle SPAR: height, diameter, ballast height, seawater height	TLP: Central column diameter, platform height, hexagon radius, ballast mass and ballast distance above sea level	
Dou et al. (2020)	SPAR	10	Support structure and mooring system	Sequential Quadratic Programming	Frequency Domain	Minimise mass (therefore cost)	Pitch motion, nacelle acceleration, natural frequencies (related to design variables), pitch angle and surge motion max and min of mooring line length as well as maximum percentage of mooring line suspended on the sea bed and design variable upper and lower bounds	SPAR: draft, upper and lower diameter. Mooring system: Length line, fairlead position and anchor radius	QuLAF and FAST
Leimeister et al. (2021)	SPAR	5	Support structure	Non-dominated Sorting Genetic Algorithm, NSGA II	N/A	Minimise motions (acceleration, inclination and translation); this in turn reduces size of platform and cost	Design variables limits, inclination angle, acceleration and transitional motion	SPAR diameter, height and ballast density	MoWiT
Leimeister et al. (2020)	SPAR	5	Support structure	Non-dominated Sorting Genetic Algorithm, NSGA II	N/A	Maintain performance (rotational stability, translational motion and nacelle acceleration) and minimise cost	Top diameter (to ensure tower fits), elevation of top diameter, upper cylinder length, and taper length all fixed, lower and upper bounds for the design variables, minimum draft, maximum inclination angle, static displacement, max nacelle acceleration	Length and diameter of the lower cylinder and ballast density	MoWiT
Sclavounos et al. (2008)	Concrete ballasted cylinder (SPAR, barge, TLP	5	Support structure, mooring system and tower	N/A	Frequency domain	Minimise nacelle accelerations	Minimum restoring force (avoids pitching more than 10 degrees), heel angle, dynamic displacements (pitch), mooring line tension should not exceed break load but cannot become slack, and cylinder design variables are constrained	cylinder radius and draft, mooring system defined by: Water depth, line tension and angle between free surface and anchor line	LINES, WAMIT, FAST

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Table 7 (*continued*).

Fylling and Berthelsen (2011)	SPAR	5	Support structure, mooring system and power take off cable	Non-Linear Programming by Quadratic Lagrangian, NLPQL	Frequency domain	Minimise SPAR, cable and mooring line costs	Heave and pitch period, mooring line tension, minimum fatigue life, SPAR buoy motion and inclination, SPAR draft, nacelle acceleration, cable curvature and tension	SPAR mass, height and diameter of each segment, thickness of bottom plate and vertical position of fairlead, mooring line and cable: Line direction, pretension, segment length, diameter and net submerged weight	MIMOSA, WAMOF3
Myhr and Nygaard (2012)	Tension-Leg-Buoy	5	Support structure and mooring system	Bound Optimization BY Quadratic Approximation (BOBYQA)	Frequency Domain and Time Domain	Reduce mooring forces and hence steel mass (cost)	natural frequency (avoid 1P and 3P), minimum mooring line tension, maximum axial stress in the space frame Mooring line: anchor radius , lower and upper mooring line diameter, yaw stiffness	Support structure: outer diameter of the lower floater part, height of the middle section below WL, lower and upper mooring line pre-strain, distance between column and turbine centre line, outer diameter of vertical columns in space frame.	3DFloat
Hegseth et al. (2021)	SPAR	10	Support structure and tower	Sequential Quadratic Programming (SQP)	Frequency domain	Minimise cost of tower and SPAR	Fatigue damage of tower and support structure, global buckling of tower, maximum platform pitch, avoid heave resonance, geometrical constraints to ensure structure is realistic	Platform and tower segment diameters and thickness and the length of the support structure segments	
Ferri et al. (2022)	Semi-Submersible	10	Support structure, mooring system	Genetic Algorithm	Time and frequency Domain	Minimise RAO (pitch, heave and surge)	Geometrical constraints, avoid natural frequencies, maximum pitch angle, maximum platform offset, minimum length of mooring cable on seabed, total mass maximum	Columns diameter, platform radius, draft, fairlead position and cable length. Anchor radius and unstretched mooring line length	FAST, ANSYS AQWA, WAMIT
Bracco and Oberti (2022)	Semi-Submersible, SPAR and TLP	5	Support structure	Genetic Algorithm	N/A	Minimise cost	Design variable bounds, metacentric height must be greater than 1 m, draft must be greater than 10 m, freeboard height must be larger than 5 m, maximum pitch angle should be lower than 5°, minimum freeboard, limited intact inclination angle of 6 and 12 for normal and survival conditions.	SPAR: Diameter, height, seawater height and ballast height. Windfloat: Diameter, Height, length, and heave plate height. Pelastar: Column height and diameter, hull diameter and depth, arm radius, and concrete volume. Windstar: Column height and diameter, arm radius and depth, and support radius	N/A
Benifla and Adam (2022)	Cylindrical body	Multi-megawatt	Support structure	Cumulative Multi-Niching Genetic Algorithm CMN GA	N/A	Reduce mass	Minimum buoyancy requirement, maximum stress occurring allowed in the structure, maximum cover angle	Cylinder length, inner and outer pipe diameters, inner and outer pipe thickness, the thickness of steel and concrete covers, angle of the covers and expansion coefficient	Ansys SOLID186, FLEX5
Lemmer et al. (2020)	Semi-submersible	10	Support structure and control system	N/A	Time domain	Maximise power, minimise nacelle acceleration and cost	Design variables and pitch natural frequency	Column spacing, heave plate height, column radius, heave plate radius, draft, steel tripod strut width and thickness, mooring line fairlead position and wind turbine controller gains	Validated with FAST, Ansys aqwa-line
Ferri and Marino (2022)	Semi-submersible	10	Support structure	Genetic algorithm	Frequency domain	Minimise tower base bending moment and platform costs	Maximum pitch 5 degrees and maximum surge motion 15% of water depth, for the catenary system at least 1/10 of the line must lie on the seabed	Column diameter, depth column, draft, platform radius, and unstretched mooring line length	FAST

characteristics will play a huge part in deciding which platform is ‘best’. For this reason, this work proposes a solution in the form of a concept selection tool. Prefiltering before the optimisation to optimise only platforms which are appropriate for the site would be hoped to reduce computational time and give realistic solutions.

The developments in the fixed offshore wind industry as mentioned in this review have already seen turbine prototypes with a capacity of up to 16 MW, with this in mind only 4% of current literature uses the IEA 15 MW turbine. For academia to make improvements it is important to keep up with industry trends, for this reason, the author’s view is to consider turbines 15 MW and greater for future work in this area.

It has been made clear through this work that cost is the main driver, being considered as the objective in 82% of current literature. The remaining literature is expected to be indirectly linked to the cost since for example reducing platform response will reduce ultimate and fatigue loads, impacting the operations and maintenance cost positively. This is an important factor in most industries since one of the main objectives is to make the technology more competitive. The other objective which was consistently found in the literature was the platform response at 52%, again this was highlighted as also being linked to the cost of energy since the response will affect not only power production but the loading experienced by the platform.

Given the importance of finding the cost accurately, several areas of improvement and further research have been identified for the cost models used within the optimisation approaches reviewed. Improvements could be made to include welding, paint, forming, and other overhead costs, with little effect on the computational time. Furthermore, by more accurately comparing the cost of different platform typologies, it is hoped that any bias created by the fact of considering all the costs proportional only to the mass of the material used could be removed. If, rather than CAPEX, the focus is on optimising the LCoE or an equivalent, a better prediction of support structure geometry which will generate the most affordable energy could be found. It has been highlighted here that there is a need for a better AEP model as well to be developed and included, to find the cost of energy of each platform.

The most common constraint was on the platform response (93%) followed by the design variables of the floating platform (79%). The importance of platform response for the overall operation of the system has been highlighted as important, hoping to improve energy production, increase the life span and reduce maintenance costs. The inclusion of constraints on the design variable is expected to seek out solutions which are feasible, manufacturable, and transportable while reducing computational time.

Since the majority of work carried out has been related to straight sided columns to make up the floating platforms, exploring less traditional shapes could seek out a cheaper option, if the models were combined with better cost models. Similarly, including the scantling design would be interesting since this would also affect the cost of the platform.

Overall the potential future improvements found from this literature review are, the flexibility to include more than one turbine size, more detailed platform modelling, and a concept selection tool. This review has highlighted how useful optimisation could be in this field however gaps within the current research have been highlighted which could be improved on to further help find the best solution for a site, considering both cost and performance to help provide more competitive green energy sources to help decarbonise the grid.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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