

Mooring control co-design for wave energy systems: Models, algorithms, and opportunities

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HIGHLIGHTS

- Presents a comprehensive assessment of WEC mooring control co-design optimisation.
- Identifies mooring requirements across different WEC device types.
- Identifies key models, controllers, design variables, and objectives for WEC mooring CCD.
- Reviews modelling and simulation software tools for implementing WEC mooring CCD solutions.
- Critically reviews the state-of-the-art, and identifies research gaps, technical challenges and future research directions.

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ABSTRACT

Control co-design (CCD) has gained popularity in recent years as a framework for optimising various design aspects of wave energy systems. The mooring system is a key component of floating wave energy converters (WECs), essential for station-keeping, but also significantly affects the overall dynamic response of a WEC. The integration of CCD with a focus on mooring optimisation presents a significant opportunity to enhance the techno-economic viability of WECs, given the substantial costs associated with mooring systems. This paper provides a comprehensive assessment of potential WEC CCD solutions for mooring optimisation, including the identification of key components of the CCD framework and the theoretical and simulation requirements for each part. Furthermore, the current state-of-the-art in WEC mooring CCD is reviewed, research gaps and technical challenges are identified, and opportunities for future research are outlined.

1. Introduction

In order to mitigate the adverse impacts of rapidly increasing anthropogenic climate change, reducing reliance on fossil fuels for power generation is imperative. While renewable energy sources (RESs) provide essential alternatives to fossil fuel-based generation, the current *green revolution* is predominantly driven by mature wind and solar technologies worldwide [1], owing not only to their green credentials but also to their comparatively lower levelised cost of energy (LCoE) relative to less mature renewable sources. Nevertheless, the growing share of wind and solar in energy systems is not without challenges, including high levels of curtailment [2], grid stability concerns [3], and the inherent intermittency of these resources. Periods of low solar and wind availability do not necessarily coincide with periods of low demand, which can undermine supply security and necessitate expensive balancing mechanisms such as large-scale energy storage or back-up

fossil-fuel generation. Enhancing renewable resource diversity through the integration of complementary RESs is therefore critical to achieving ambitious targets for a 100% renewable energy future [4].

To this end, wave energy presents substantial potential [5], estimated at between 16,000 to 18,500 [TWh/yr] [6], and offers complementary advantages to other RESs [7,8]. Wave energy converters (WECs), devices that harvest energy from ocean waves, have been developed in a variety of concepts to exploit this vast marine resource [9]. However, the commercial viability of wave energy remains elusive [10], largely due to the relatively high LCoE compared to more mature RESs, such as wind and solar. A promising pathway for reducing wave energy LCoE involves the integration of advanced control system technologies, which have been shown to have a dramatic effect on WEC system dynamics, and energy conversion performance [11]. The objective of WEC control is to maximise energy absorption from ocean waves through

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the active manipulation of device motion [12]. By enabling fuller utilisation of installed infrastructure, effective WEC control strategies can enhance energy capture and, ultimately, reduce the economic cost of wave energy.

1.1. Motivation

The mooring system is essential for maintaining station-keeping and operational reliability of offshore WECs. In contrast to mooring systems employed in the oil and gas sector, which serve *only* a station-keeping function, those designed for WECs must also accommodate additional dynamic loads. These loads arise from various factors, including the energetic sea conditions of deployment sites, which are selected specifically to maximise energy extraction from ocean waves, as well as the application of control strategies aimed at enhancing energy capture. Such control approaches typically exaggerate device motion by operating it in resonance with incoming wave conditions [13], leading to significantly increased loading on the mooring system. Moreover, the dynamic behaviour of the mooring system can influence device motion in both beneficial and/or detrimental ways, ultimately affecting the overall dynamic response of the WEC [14]. However, despite this significant effect on the overall WEC dynamics, the role of mooring dynamics is frequently *underappreciated* in control-focused research on WECs. Mooring effects are often overlooked, or represented with simplified linear models [15], primarily due to the inherent nonlinear complexity of mooring dynamics [16].

Just as mooring dynamics are frequently underappreciated in the control design of WECs, the converse is also true: WEC control systems are often neglected within the conventional *sequential* approach to mooring system design [19,20]. This mutual disconnect is a defining feature of the traditional sequential design methodology, as depicted in Fig. 1(a). Control co-design (CCD) presents a more integrated alternative, whereby the physical parameters of the system are designed in parallel with control system considerations from the outset of the design process, constituting a fundamentally *control-informed* design approach. This is particularly important where the performance of the overall system is significantly affected by control, as is the case in wave energy systems. Fig. 1(b) illustrates three CCD architectures including iterative, nested and simultaneous design [17,18]. As demonstrated in [20], integrated CCD methods, such as the nested or simultaneous architectures depicted in Fig. 1(b), are generally unsuitable for WEC applications, primarily due to the limited transparency of WEC dynamic models. Consequently, the iterative CCD approach is more commonly adopted in the WEC literature to optimise various physical components, including device geometry [21], power take-off (PTO) systems [22], and WEC array layouts [23]. In contrast, the application of CCD to WEC mooring system design remains largely under-explored. This is primarily due to the complex and nonlinear dynamics of mooring systems, the diversity of mooring configurations, and the use of disparate software environments for mooring analysis and control system design. Furthermore, to the best of the authors' knowledge, no existing study

has undertaken a comprehensive assessment of WEC CCD for mooring system optimisation, encompassing both theoretical aspects and the possible implementable simulation frameworks.

1.2. Objectives

In light of the identified disconnect between control and physical system design in WEC mooring applications, and the limited attention given to WEC mooring CCD methodologies, a comprehensive evaluation of CCD in this context is both timely and necessary. Building on the preceding discussion, this paper presents a comprehensive assessment of CCD for mooring system optimisation in WEC applications. The primary objectives, and contributions, of this study are outlined as follows:

- Identification of the key components of WEC CCD for mooring optimisation, including
 1. appropriate mathematical models for both WEC and mooring systems,
 2. suitable control strategies for control performance evaluation,
 3. mooring system design parameters to be optimised, and
 4. objective (performance) functions for design evaluation.
- Identification of mooring requirements for various WEC types.
- Review of existing modelling and simulation software tools for WEC mooring CCD implementation.
- Critical review of the current state-of-the-art in WEC CCD applied to mooring system optimisation, highlighting research gaps and technical challenges.
- Propose clear and actionable future research directions, based on a critical analysis of the literature.

1.3. Paper layout

The remainder of the paper is organised as follows: Section 2 introduces CCD framework fundamentals, along with various aspects of the WEC CCD paradigm. Section 3 provides an overview of existing WEC classifications and presents a novel classification scheme based on mooring requirements. Section 4 examines each component of WEC mooring CCD optimisation in detail, including the dynamics of both WEC and mooring systems, control strategies, common mooring configurations and their associated design parameters, and performance functions for design evaluation. Section 5 presents various potential software tools for implementing WEC mooring CCD solutions. Section 6 reviews the existing literature on WEC mooring CCD studies and identifies key research gaps. Section 7 outlines major challenges and offers an outlook for future research. Finally, Section 8 concludes this study.

2. Fundamentals of control co-design

CCD refers to the concurrent design of a system physical components and the associated control system, ensuring that both are optimised in unison, rather than through a sequential process (see, for example,

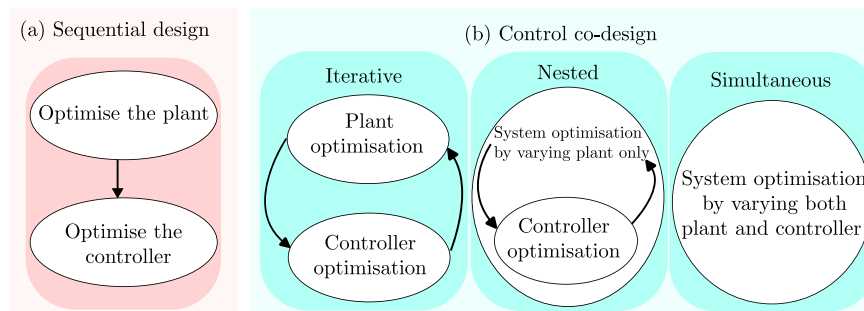


Fig. 1. Design approaches: (a) Traditional sequential design approach, and (b) control co-design approaches. Adapted from [17,18].

Fig. 1). Within a CCD framework, the control system assumes a central role, which is particularly critical for multidisciplinary systems comprising multiple interacting subsystems [24]. By accounting for these interactions from the outset, CCD facilitates a more integrated and effective approach to system design. Wave energy systems present a prime example of such multidisciplinary complexity, involving hydrodynamics, mechanical engineering, electrical engineering, and control systems, all of which must be co-optimised to achieve overall optimal performance.

2.1. Elements of a WEC CCD framework

In general, a WEC CCD problem can be formulated [20] as:

$$\begin{aligned} & \text{Optimisation parameter(s)} \rightarrow \rho^{\text{opt}} \leftarrow \text{Optimise}_{\rho \in \mathbb{R}^N} \Upsilon \quad \text{Objective function} \\ & \text{subject to: Optimise } \mathcal{J}(\rho) \quad \text{Control objective} \\ & \quad \quad \quad \mathcal{C} \quad \text{and} \quad \Sigma \quad \text{Constraints set} \quad \text{System dynamics} \end{aligned} \quad (1)$$

The annotated components in (1) represent the key elements of a WEC CCD formulation. Each part of (1) is discussed in detail in Section 4.

A typical example of an *iterative* WEC CCD workflow is illustrated in Fig. 2. The CCD process begins with the specification of design parameters, which vary depending on the particular CCD application (see, e.g., Fig. 3). For instance, in the geometric optimisation of a cylindrical point absorber WEC, the device radius may serve as a design parameter [21], whereas in WEC array layout optimisation, the separation distance between WEC units is a key design parameter [23]. Once these physical parameters are defined, control performance is evaluated for the specified design configuration. The overall system performance is then assessed against a chosen criterion, typically a *cost*-related metric. If the design is deemed suboptimal, the parameters are updated and the process is repeated. This *iterative* loop continues until a satisfactory or optimal solution is obtained.

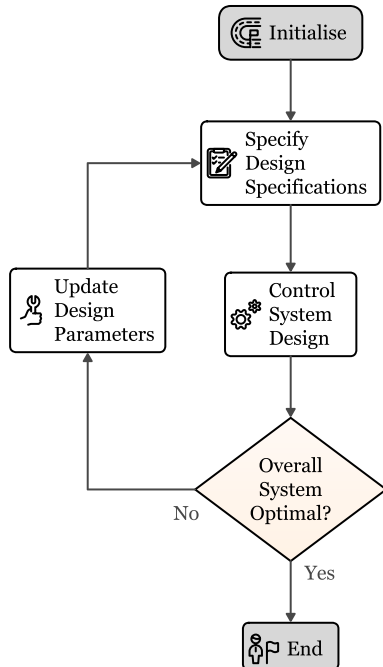


Fig. 2. A typical WEC CCD process.

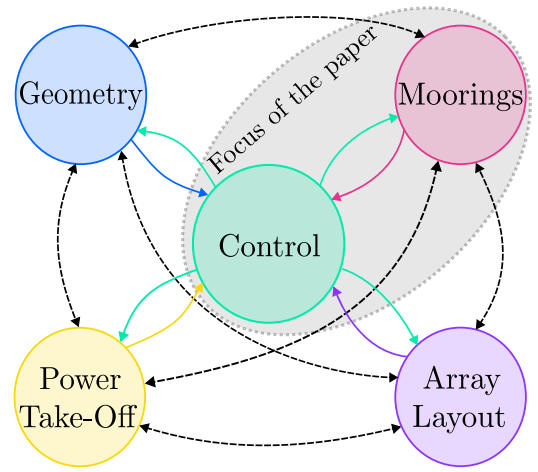


Fig. 3. Aspects of WEC control co-design.

2.2. Aspects of WEC CCD

Given the strong influence of energy-maximising WEC control on device performance, WEC CCD is widely recognised as a key enabler for the economic competitiveness of wave energy technology [20]. WEC CCD is increasingly regarded as an essential facet of holistic wave energy system design. Various aspects of WEC CCD have been explored in the literature, including device geometry [21], PTO system [22], WEC array layout [23], and mooring system [25], as illustrated in Fig. 3. It is important to note that the optimal design of one subsystem via CCD often influences the design of others. These interdependencies are highlighted in Fig. 3 through connecting arrows. For example, the optimal geometry design of a WEC affects the performance requirements and design of the PTO system, and vice versa.

Ideally, a *global* WEC CCD framework would simultaneously consider all aspects of WEC design. However, this paper focuses specifically on CCD for mooring optimisation for two key reasons: (1) a global CCD formulation remains computationally infeasible with current tools and methods, and (2) WEC mooring optimisation is still in its infancy, requiring substantial progress before it can be meaningfully integrated into a broader global WEC CCD framework. As such, this study takes a focused approach by identifying the specific challenges and opportunities associated with WEC mooring CCD optimisation, thereby contributing to a necessary foundation for future progress towards global CCD for wave energy systems.

3. WEC classification and mooring considerations

Typically, a WEC consists of a wave absorber, which is responsible for capturing wave energy from ocean waves, and a PTO mechanism that converts the resulting mechanical energy into useful (usually electrical) energy. WEC technology is rapidly evolving, with a wide range of WEC concepts existing at various technology readiness levels (TRLs) [10]. However, there is still no consensus on a dominant technology for efficient wave energy extraction. Over the years, numerous classification schemes have been proposed, categorising WECs based on different criteria, such as operating principle, directional characteristics, proximity to the coast, and PTO systems. Notable examples include classifications proposed by Budal and Falnes [26], Hagerman and Heller [27], Falnes and Løvseth [28], Falcão [29], and López et al. [9], among others. A comprehensive review of these classifications is provided in [30] and summarised in Fig. 4. The classification of WECs remains a complex topic, further complicated by the fact that many devices can simultaneously fit into multiple categories within different classification frameworks.

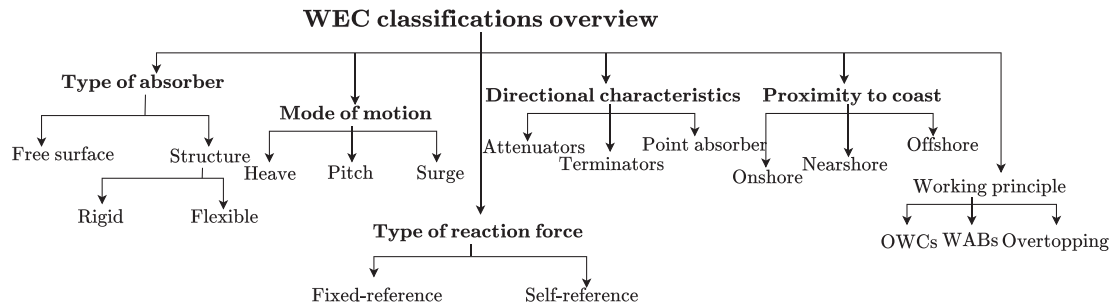


Fig. 4. Overview of various WEC classification approaches.

Like WECs, numerous mooring systems have been developed over the years for a range of offshore applications, including oil and gas platforms and other marine renewable energy devices. Generally, a WEC mooring system, like that of any other moored marine structure, consists of three main components: mooring lines, anchors, and connectors. Additional elements, such as clump weights and buoys, can also be attached to the mooring lines. The lines themselves may be constructed from different materials, including chains and ropes (wire or fibre), which influence key system properties such as inertia, damping, and stiffness [31]. Anchors, on the other hand, provide a fixed attachment point on the seabed for the mooring lines, and may take several forms, e.g., pile, dead weight, or drag embedment [32]. Based on their geometric configuration, WEC mooring systems can be broadly classified into single-point mooring (SPM), and spread mooring, systems (see, e.g., Section 4.3.1 for further details on WEC mooring configurations). Typically, there is strong coupling between the response of a device, and its mooring system [33], which can result in large, potentially resonant, motion. Unlike conventional offshore structures, which are designed to avoid such responses, WECs are often designed to exploit resonance to maximise power extraction in one or more modes of motion [34]. Therefore, a clear understanding of the mooring requirements, associated with different WEC types, is essential before the design stage.

While substantial attention has been devoted to the various ways of classifying WECs, comparatively little focus has been placed on the choice of mooring systems within these classifications, i.e., classifying WECs according to their mooring requirements. To the best of the authors' knowledge, only three studies have explicitly examined this aspect, either by proposing mooring-based WEC classification or by analysing the types of mooring systems suited to specific WEC configurations. These include the classifications proposed by Harris et al. [35], Johanning et al. [34], and Price [36]. The first of these, by Harris et al. [35], introduces a mooring selection framework for WECs based on their location (i.e., proximity to the coast, as shown in Fig. 4), directional characteristics, and operating principle. Their approach highlights that axi-symmetric devices (e.g., point absorbers), being non-directional, are suited to spread moorings, whereas directional devices, such as terminators and attenuators, require single-point moorings to align with the prevailing wave direction. The authors, in [35], further associate on-shore devices with fixed caissons, nearshore devices with fixed towers or caissons, and offshore devices with slack moorings. However, associating mooring type primarily with location, as in [35], can be misleading, as argued by Price in [36]. For example, while shoreline devices must rely on a fixed reference to the seabed, self- (inter or intra-body) referenced devices can also be viable in nearshore waters, contrary to the assumptions implicit in [35].

Secondly, Johanning et al. [34] propose a classification of mooring requirements by categorising WECs as either *motion-dependent* or *motion-independent*. However, this framework is relatively imprecise, as it conflates absorber motion with reaction force behaviour, and does not explicitly identify the characteristics that determine mooring requirements. For instance, the *motion-dependent* category encompasses

all types of wave-activated bodies, regardless of whether their reaction mechanism is fixed, or self-referenced. Such ambiguity can result in inconsistent or unrealistic mooring interpretations, since mooring requirements for bottom-referenced WECs differ significantly from those of self-referenced systems. For example, within this framework, it is conceivable to apply a catenary mooring to a WEC where the PTO is already referenced to the seabed, such as a heaving point absorber with a direct-drive PTO, which would unnecessarily constrain the buoy motion.

To address the limitations of earlier frameworks, Price [36] introduces a more comprehensive classification system for WECs, structured around the various stages of power flow within different WEC power-trains. A key component of this framework concerns the *means of reaction*, equivalent to the *type of reaction force* used in earlier classifications [27], which defines the relative motion between the primary wave absorber and a reference point. This classification is particularly relevant when assessing mooring system requirements, as the reaction mechanism fundamentally governs the nature and magnitude of forces transmitted through mooring lines and anchoring systems. In this classification, reaction mechanisms are categorised into three categories, including fixed, referenced, and inertial. However, in this approach both inertial and referenced can be categorised into one self-referenced category, i.e., either the absorber is referenced to a neighbouring body or an inertial component inside the absorber hull. In addition, directional characteristics, which strongly influence mooring requirements and station-keeping behaviour, are not explicitly considered in this classification framework.

Building on the foundations laid by Harris et al. [35], Johanning et al. [34], and Price [36], this study proposes a refined classification framework linking WEC operational principles to mooring system requirements, detailed in Table 1. By explicitly accounting for both the reaction mechanism and directional behaviour, it provides a comprehensive basis for understanding how the WEC type influences mooring configuration and design considerations. This is particularly useful for cases in which different mooring concepts may be feasible at the same site, or where the mooring design is governed by device motion and reaction mechanism rather than by location alone. In this classification, WECs are categorised into three main categories:

► **Seabed-coupled WECs:** As the name suggests, this category includes devices that are coupled to the seabed and can be further categorised into rigidly coupled devices (through the WEC structure) or tension-dominated devices (using tension legs or taut moorings). Typical WEC devices within the seabed-coupled category include onshore/nearshore OWCs, bottom-fixed flaps, bottom-fixed cyclorotors and bottom-referenced-fixed point absorbers. Examples include the Atargis CycWEC [37] for fixed coupling and the CorPower WEC [38] for a bottom-referenced, taut-moored device. For rigidly fixed, seabed-coupled, WECs, mooring lines are primarily provided for redundancy/safety purposes, with loads transferred through the WEC structure itself. Conversely, for tethered or tension-dominated, bottom-referenced WECs, the mooring

Table 1

Proposed classification of WECs by mooring requirements.

WEC category	Reaction mechanism	Directional behaviour	Mooring type	Representative examples	Mooring design implications
Seabed-Coupled	Rigidly Fixed	Directional	Foundation, piles, or gravity-based	Oyster [46], CycWEC [37]	Mooring mainly for redundancy; loads are transferred directly through the foundation to the seabed.
	Tethered/ Tension-dominated	Omnidirectional	Taut or tension-leg mooring	CorPower WEC [38], Infinity WEC [47]	Mooring provides vertical reaction and depth control; tension stiffness influences the device natural frequencies and motion response.
Freely-Floating	Self-reference (inter and intra-body)	Highly directional	Single-point mooring (SPM or turret)	Pelamis [40], M4 WEC [39],	Mooring enables weathervaning; its geometry directly affects hydrodynamic alignment and energy capture.
	Self-reference (inter and intra-body)	Omnidirectional or adaptive	Spread or slack mooring	PowerBuoy [41], ISWEC [42]	Mooring ensures station-keeping or limited excursion; stiffness and layout strongly influence dynamic coupling and fatigue loads.
Semi-Coupled	Hybrid mechanism combining seabed coupling and floating motion.	Partially directional	Hybrid (compliant + slack)	WaveSub [43], Sharp Eagle [44]	Mooring interacts dynamically with PTO motion; requires careful balance between compliance and restraint.

system actively affects power absorption, as the tension influences the WEC natural frequency.

- ▷ **Freely-floating WECs:** This category includes self-reacting (inter-body or inertial) floating WECs. Depending on the directional characteristics, freely-floating WECs can be further categorised into directional and non-directional (or omnidirectional) sub-categories, since the directional characteristics have implications for the chosen mooring system. Whilst directional floating WECs, such as the M4 WEC [39] and Pelamis (attenuator) [40], require mooring that allows weathervaning properties, SPM or turret moorings are the appropriate choice for such devices. Conversely, omnidirectional floating WECs, such as the PowerBuoy [41] or ISWEC [42], do not require such weathervaning properties, so spread or slack moorings are the appropriate choice.
- ▷ **Semi-coupled WECs:** This category includes WECs which have hybrid reaction mechanisms, i.e., combining both seabed and floating (self) reactions. Typical WECs in this category include multi-body systems (e.g., WaveSub [43], the Sharp Eagle WEC [44]) and hybrid wind-wave systems [45]. Typically, the mooring system provides both restraint and compliance, often using hybrid (taut + slack) systems, and the mooring system interacts dynamically with PTO and control systems.

Encompassing seabed-coupled, freely-floating (directional and non-directional), and semi-coupled devices, the proposed classification scheme unifies and extends previous classifications [34–36], thereby offering a simple, intuitive and inclusive foundation for selecting and evaluating mooring systems across diverse WEC technologies and deployment conditions.

4. Control co-design for mooring optimisation in wave energy systems

This section provides a detailed examination of the various components of a WEC mooring CCD framework, as outlined in (1).

4.1. WEC hydrodynamic modelling

In this section, we revisit key concepts in WEC hydrodynamic modelling. Rather than providing an exhaustive review of the wide range of WEC modelling strategies available in the literature, the focus here is on fundamental principles and the identification of models suitable for WEC mooring CCD applications. For comprehensive reviews on WEC modelling, readers are referred to [48,49].

To identify suitable WEC models for mooring co-design, it is essential to first clarify the modelling requirements. For instance, in mooring co-design, dynamic models must accurately represent the coupling between the WEC and mooring system dynamics. Additionally, these models should be control-oriented to facilitate controller design and evaluation. In other words, the model must capture all major dynamic couplings while remaining sufficiently simple to support control system analysis and design [17].

Hydrodynamic WEC models can be broadly classified into two categories:

- ▷ **Physics-based models:** These models are derived from first principles and have a clear physical interpretation. Physics-based, control-oriented WEC models are typically simplifications of the Navier–Stokes (NS) equations [50], which govern fluid motion and fluid–structure interactions. The conservation of mass and momentum can be expressed, using the NS-equations, as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}_f) = 0, \quad (2a)$$

$$\frac{\partial \mathbf{v}_f}{\partial t} + \mathbf{v}_f^T \nabla \mathbf{v}_f = \mathbf{f} - \frac{1}{\rho} \nabla p_r + \frac{\mu_f}{\rho} \nabla^2 \mathbf{v}_f. \quad (2b)$$

Here, ρ , $\mathbf{v}_f$, p_r , $\mathbf{f}$ and μ_f denote the fluid density, velocity field, pressure, external force per unit mass, and viscosity, respectively. In addition, the operators ∇ , ∇ and ∇^2 refer to the divergence, gradient, and Laplacian, respectively. A numerical discretisation method is required to obtain a solution, since there is no analytical solution to the NS equations. Therefore, numerical modelling approaches, such as computational fluid dynamics (CFD) and smoothed-particle hydrodynamics (SPH), are commonly used to approximate NS equations, in the literature [51]. However, CFD based modelling methods are computationally expensive and they cannot be used for control purposes, not least due to their non-parametric form.

By simplifying the system of Eq. (2), under potential flow (PF) assumptions [52], as shown in Fig. 5, PF theory avoids the computational cost associated with CFD-based solutions of hydrodynamic wave–structure interactions. These PF assumptions include that the fluid is inviscid and that the flow is irrotational and incompressible. Under these assumptions, the governing equation of motion can be expressed, using Newton's second law, as:

$$m\ddot{z}(t) = f_g + f_{\text{hydro}}(t) + f_{\text{ext}}(t), \quad (3)$$

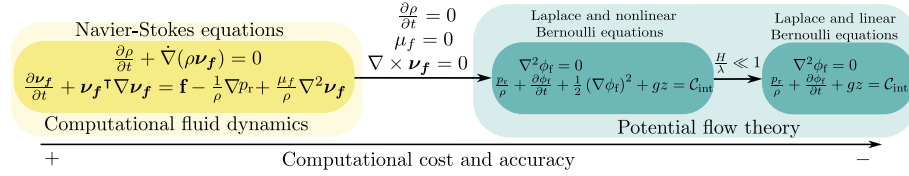


Fig. 5. Governing equations for various WEC hydrodynamic models. Adapted from [10].

where f_g is the force due to gravity, and $f_{\text{hydro}}(t)$ represents the total hydrodynamic forces acting on the body. The term $f_{\text{ext}}(t)$ includes external forces, such as the PTO control force $f_u(t)$ and the mooring force $f_m(t)$. The hydrodynamic force $f_{\text{hydro}}(t)$ can be computed as the surface integral of the pressure p_r over the wetted surface S :

$$f_{\text{hydro}}(t) = \iint_S p_r \mathbf{n} dS, \quad (4)$$

where $\mathbf{n}$ is the normal vector to the surface element dS . Thus, p_r is the key parameter for hydrodynamic modelling. Under PF theory, the pressure p_r can be computed either by solving the Laplace equation together with the *nonlinear* Bernoulli equation (also referred to as fully nonlinear potential flow (NLPF) theory), shown in Fig. 5, and evaluating the velocity potential ϕ_f ; or by solving the Laplace equation with the *linear* Bernoulli equation (i.e., linear potential flow (LPF) theory [53]), also shown in Fig. 5, by further assuming that the wave height is much smaller than the wavelength and that device motions are small. Under the LPF assumptions, the total velocity potential can be expressed as the superposition of the incident ϕ_i , diffraction ϕ_d , and radiation ϕ_r potentials, such that

$$\phi_f = \phi_i + \phi_d + \phi_r. \quad (5)$$

Typically, mesh-based boundary element method (BEM) tools, such as WAMIT [54] or NEMOH [55], are utilised to evaluate the potential ϕ_f by considering *linear* boundary conditions [52], and compute the main hydrodynamic parameters.

Consequently, Eq. (3), in the time-domain, can be reformulated into the linear Cummins' equation as:

$$(M + m_\infty)\ddot{z}(t) = -K_h z(t) - k_r(t) * \dot{z}(t) + k_e(t) * \eta(t) + f_{\text{ext}}(t), \quad (6)$$

where the excitation force is given by $f_e(t) = k_e(t) * \eta(t)$, with the excitation impulse response function (IRF) $k_e(t)$; the radiation force due to body motion is given by $f_r(t) = -m_\infty \ddot{z}(t) - k_r(t) * \dot{z}(t)$, where m_∞ is the added mass at infinite frequency and $k_r(t)$ is the radiation IRF; and the linearised hydrostatic restoring force is given by $f_h(t) = -K_h z(t)$, with K_h denoting the hydrostatic stiffness coefficient. The symbol $*$ represents the convolution operator. The $k_e(t)$ and $k_r(t)$ IRFs can be calculated from the solution provided by BEM solvers. Generally, a parametric LTI representation is obtained for the non-parametric radiation kernel $k_r(t)$ to get a linear state-space representation of the WEC hydrodynamics appropriate for control design. While such linear representations are widely used in WEC control studies, it has been shown that, under controlled conditions, the use of linear physics-based models, typically derived under LPF assumptions, can lead to a violation of their underlying assumptions, resulting in the so-called *modelling paradox* [13]. In order to avoid such a scenario, various nonlinear extensions of the Cummins'-based models are proposed in the literature, which include various nonlinearities, such as viscous drag [56], nonlinear restoring forces [57] and mooring forces [58]. However, it is important to note that the inclusion of dominant nonlinear forces is highly dependent on WEC geometry and application scenarios and, therefore, must be addressed on a case-by-case basis [49,59,60]. Accounting for the dominant *critical* nonlinear forces in (6) yields a comparatively higher-fidelity model at a modest computational cost. From a mooring CCD perspective, a consideration

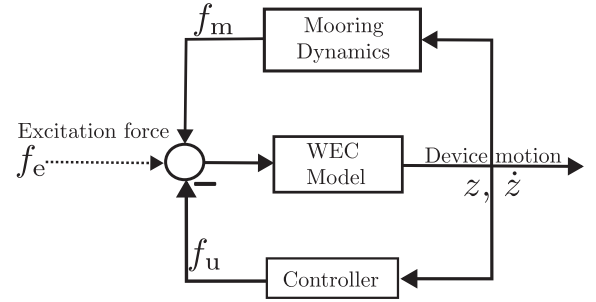


Fig. 6. Block diagram of possible coupling between the WEC and the associated mooring system.

is what level of computational challenge can be tolerated, considering the need to simulate WEC, PTO, moorings and control in a co-design formulation.

It is important to note that mooring dynamics are inherently nonlinear, although some linear versions are also available (see, e.g., Section 4.3.2), and incorporating them into control-oriented WEC models in a tractable manner may be challenging, since mooring dynamics are generally evaluated using dedicated mooring solvers (see Section 5 for a discussion of available tools). As a result, mooring dynamics are often excluded from the WEC control literature, with some notable exceptions (e.g., [58,61,62]). However, for WEC mooring CCD applications, it is necessary to couple mooring dynamics with the WEC model. This coupling is typically achieved by treating $f_m(t)$ as an external force in (3) (see, e.g., Fig. 6), where $f_m(t)$ is either calculated numerically using a mooring solver or approximated using a data-based, parameterised representation, as demonstrated in [62]. It is worth noting that, in general, mooring forces are not independent of device motion and, therefore, may not be fully considered 'external' (exogenous).

► **Data-based models:** These models are derived from numerical or experimental data and range from black-box models (with no physical interpretability) to various levels of grey-box models, where each *shade* of grey corresponds to the degree of physical insight embedded in the model [63]. Given the computationally intensive nature of CCD applications, data-based *surrogate* models of varying fidelity are often employed to reduce the computational burden (see, for example, Section 6 of Ringwood [20] for a comprehensive overview of surrogate models in WEC CCD).

In the context of WEC mooring CCD, data-based surrogate models for moored WECs are also valuable for mitigating the computational overhead associated with using separate tools for WEC and mooring dynamics (see, e.g., Fig. 6), which are typically modelled in different software environments. However, it is essential to exercise care in generating training data (numerical or experimental) for such models to ensure a proper trade-off between model accuracy and computational efficiency [64].

Implications for WEC mooring CCD. Fig. 7 illustrates control-oriented WEC models suitable for CCD applications, encompassing both physics-based and data-driven approaches. Physics-based models include both

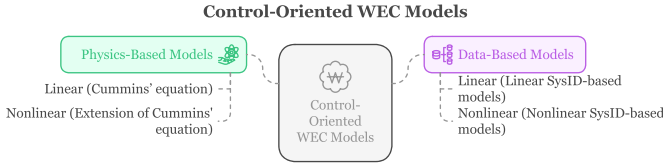


Fig. 7. Control-oriented WEC models appropriate for WEC mooring CCD.

linear Cummins' equation formulations and their nonlinear extensions. Data-driven models, on the other hand, can also be linear or nonlinear depending on the structure of the selected system identification (SysID) method. A comprehensive review of data-driven control-oriented WEC models, covering both time-domain and frequency-domain SysID techniques, is provided in [65]. From a CCD perspective, the choice of model depends on the stage of the design process and the required balance between accuracy and computational cost. High-fidelity (e.g., CFD etc.) nonlinear WEC models are most appropriate for final design verification and performance assessment, where accurate prediction of coupled WEC–mooring dynamics is essential. In contrast, both physics and data-driven linear and nonlinear models (see, e.g., Fig. 7) are generally more suitable for optimisation and control design, owing to their lower computational burden. Data-driven surrogate models provide an attractive solution, particularly for computationally intensive CCD studies involving repeated simulations, as they can significantly reduce evaluation times while retaining acceptable accuracy. Future developments in efficient surrogate modelling and reduced-order representations of coupled WEC–mooring systems are likely to play an important role in enabling large-scale CCD studies and, ultimately, reducing WEC LCoE through more computationally tractable optimisation frameworks.

4.2. WEC control fundamentals

The choice of WEC controller in a WEC CCD framework has implications for optimal design [21] and simulation requirements. Therefore, WEC control philosophy selection is an important consideration in a CCD framework. In order to select a WEC control philosophy for a CCD solution, we first need to understand all the options available. To this end, in the following, we recall some fundamental concepts of WEC control and the possible control structures.

Ideally, the principal control objective in a WEC controller is to minimise the LCoE, defined as

$$\text{LCoE} = \frac{\text{CapEx} + \text{PV}(\text{OpEx})}{\text{PV}(E_c)}, \quad (7)$$

$$\text{PV}(Q) = \sum_{y_r=y_r^0}^{Y_r} \frac{Q(y_r)}{\left(1 + \frac{R_d}{100}\right)^{y_r}},$$

where CapEx, OpEx, and E_c represent capital expenditure, operational expenditure, and captured energy, respectively. R_d denotes the discount rate, and Y_r represents the project duration in years. The term $\text{PV}(Q)$ refers to the present value of a given quantity, Q . In practice, however, LCoE is often reformulated into more tractable objectives, such as maximising energy capture, mainly because of the considerable uncertainty in estimating OpEx. This uncertainty arises mainly from the lack of long-term operational data from real-sea deployments. Hydrodynamic WEC controllers therefore typically aim to manipulate device motion to maximise absorbed energy from ocean waves, thereby leveraging the installed capital infrastructure. The general energy-maximising WEC control problem can be informally posed as follows [12]:

Maximise $J_u(t)$ Energy absorption from incoming waves,
Subject to: WEC dynamics and physical constraints.

From a mathematical perspective, the absorbed energy $\mathcal{E}$ over a finite time interval $[0, T]$, where $T \in \mathbb{R}^+$, can be expressed as:

$$\mathcal{E} = \int_0^T P_{\text{abs}}(t) dt, \quad (8)$$

where $P_{\text{abs}}(t) = v(t)f_u(t)$ denotes the instantaneous absorbed mechanical power.

Within the wave energy control literature, one of the most fundamental results is a relatively simple solution to the problem of maximising energy extraction from WECs. At the core of this solution lies the impedance-matching (IM) principle, which is typically formulated in the frequency domain. By applying the Fourier transform to the linear Cummins equation in (6), and considering $f_{\text{ext}}(t) = f_u(t)$, the frequency-domain representation of the WEC is obtained as:

$$j\omega(M + m_\infty)\dot{Z}(\omega) + K_r(\omega)\dot{Z}(\omega) + \frac{K_h}{j\omega}\dot{Z}(\omega) = F_e(\omega) - F_u(\omega), \quad (9)$$

where $F_u(\omega)$ and $\dot{Z}(\omega) = V(\omega)$ denote the Fourier transforms of the PTO force (control input) and the device velocity, respectively. From (9), the following relation is obtained:

$$V(\omega) = G(j\omega) [F_e(\omega) - F_u(\omega)] = \frac{1}{Z_i(\omega)} [F_e(\omega) - F_u(\omega)], \quad (10)$$

with $Z_i(\omega)$ defined as:

$$Z_i(\omega) = B_r(\omega) + j\omega \left(M + A_r(\omega) - \frac{K_h}{\omega^2} \right), \quad (11)$$

representing the *intrinsic impedance* of the WEC. Here, $G(j\omega)$ is the frequency-domain transfer function of the WEC dynamics. The concept of intrinsic impedance closely resembles the well-known ‘internal impedance’ used in electrical circuit theory. Hence, the WEC system can be equivalently represented by an electrical circuit model, as illustrated in Fig. 8(a). In this analogy, the PTO behaves as a dynamic load, and the control force $F_u(\omega)$ is designed to maximise power transfer to this load. According to the IM principle, from circuit theory [65], maximum power transfer occurs when the load impedance $Z_{\text{pto}}(\omega)$ is equal to the complex conjugate of the source impedance $Z_i(\omega)$. Thus, the optimal control force is given by:

$$F_u(\omega) = Z_{\text{pto}}(\omega)V(\omega) = Z_i^*(\omega)V(\omega), \quad (12)$$

where $Z_i^*(\omega)$ denotes the complex conjugate of $Z_i(\omega)$. Equivalently, the IM condition can be expressed in terms of the optimal velocity profile, formulated as a purely real transfer function that enforces zero phase difference (i.e., phase-locking) between the velocity $V(\omega)$ and the excitation force $F_e(\omega)$:

$$V^{\text{opt}}(\omega) = \frac{1}{Z_i(\omega) + Z_i^*(\omega)} F_e(\omega) = \frac{1}{2B_r(\omega)} F_e(\omega). \quad (13)$$

Eqs. (12) and (13) together define the well-established IM, or *complex-conjugate*, condition [53].

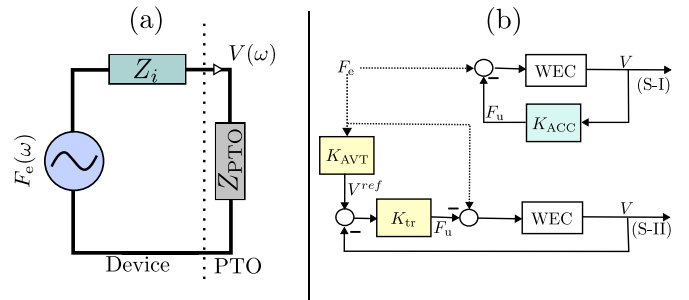


Fig. 8. Impedance matching (IM) principle: (a) equivalent circuit representation, (b) alternative typical WEC control structures.

Table 2

WEC controllers appropriate for WEC CCD applications. OB: Optimisation-based, !OB: Non-optimisation-based, Pos.: Position, Vel.: Velocity, MPC: Model predictive control.

WEC controller	Type		Constraints			CCD application			
	OB	!OB	Pos.	Vel.	Force	Geometry	PTO	Layout	Mooring
Simple and effective [70,73,74]		•	•			•		•	
LiTe-Con [75]		•	•						
Symphony [76]		•	•		•				
MPC & MPC-like ¹ [68,77]	•		•	•	•	•	•		•
Half-wave MPC [71]	•		•	•	•	•			

¹ Spectral/Pseudospectral and Moment based optimal controllers.

While the IM principle provides a theoretical foundation for energy-maximising WEC controllers, several practical challenges must be addressed before it can be implemented, such as non-causality, safety constraint handling, reactive power requirements [66], and the ability to deal with broadband (panchromatic) wave excitation. These issues are not discussed here for brevity, as they have been addressed in detail elsewhere (see, e.g., Ringwood et al. [11]). To yield feasible control solutions, IM-based *simple* controllers [67] often simplify the WEC control problem using a band-limited frequency-domain approximation. Similarly, optimisation-based WEC controllers [68] approximate the infinite-dimensional control problem using a finite set of basis functions, such as zero-order hold in model predictive control (MPC), or Fourier basis functions in spectral or moment-based control frameworks. Regardless of these simplifications, most WEC controllers can be categorised into one of three general control structures,¹ as illustrated in Fig. 8(b):

- S-I:** Approximate complex conjugate (ACC) structure, and
- S-II:** Approximate velocity tracking (AVT) structure.

Regarding the selection of suitable WEC controllers for WEC mooring CCD applications, it is crucial to identify the specific issues associated with CCD and the relevant WEC control methodologies that can be applied. The choice of energy-maximising WEC control philosophy directly influences the outcome of the optimal design process within a CCD framework, as highlighted in [23,69]. Since CCD is a design-stage methodology, the controllers need not be suitable for real-time implementation; instead, all that's required is their *control performance*, evaluated to guide the design optimiser (see, for example [70,71]). Consequently, challenges related to real-time implementation, such as excitation force estimation and prediction, are not considered in this context. However, computational efficiency remains a critical requirement, particularly when designing shared mooring systems for WEC arrays, where the computational burden of optimisation grows significantly with the number of devices [72]. Another key consideration when selecting WEC controllers for CCD is their ability to accommodate constraints, such as limits on position, velocity, and PTO (control) force, which are essential for ensuring the safe operation of WECs.

To this end, Table 2 summarises a selection of WEC controllers that are considered appropriate for WEC CCD applications (though not necessarily in the context of mooring system design). The criteria for evaluating suitable control methodologies are based on whether they are optimisation based (OB) or not (!OB), which has direct implications for computational efficiency. OB WEC controllers require an additional optimisation loop within the overall CCD design loop (see, e.g., Fig. 2). The evaluation also considers their ability to accommodate different types of constraints, and whether they have been implemented across the various CCD sub-problems, namely geometry optimisation, PTO design, array layout optimisation, and mooring system design. It is worth noting that other WEC controllers exist in the literature, some of which have been

applied to CCD studies. Examples include passive damping [21,78] and reactive proportional–integral (PI) / proportional–derivative (PD) controllers [25]. These controllers are not included in Table 2, however, as they do not feature explicit constraint-handling mechanisms. In addition, a recently proposed bi-conjugate IM controller [79], developed specifically for co-design applications, provides a means of incorporating PTO dynamics into the IM condition, thereby establishing an electrical energy maximisation framework. Nevertheless, the bi-conjugate IM controller is also excluded from Table 2, since it suffers from the same limitations as the *original* IM condition (12), namely the inability to address both panchromatic sea states and constraints.

!OB controllers are typically more computationally efficient and therefore attractive for CCD problems, although they offer limited constraint-handling capabilities. As seen in Table 2, only one !OB controller, the simple and effective controller [73] (and its variation for WEC arrays [70,74]), has been utilised in a CCD context. This presents an opportunity to explore other simple (!OB) controllers, such as LiTe-Con and Symphony, for CCD applications, including mooring optimisation. In contrast, OB controllers, such as MPC and MPC-like approaches, generally provide greater flexibility in handling constraints (position, velocity, and force). However, this often comes with a significant computational burden, which may limit their applicability in large-scale CCD studies. Nonetheless, in cases where constraints form a core part of the design problem, for instance in PTO CCD [22], the use of an OB controller is essential. Of particular interest is the algebraic half-wave MPC [71], developed specifically for CCD applications, which delivers performance comparable to MPC (pseudospectral) controllers to within a 5% margin of error, yet requires only a fraction of the computational effort.

Implications for WEC mooring CCD. With regard to WEC mooring CCD applications, it is worth noting that only one control methodology from Table 2 has been applied. This reflects the current lack of studies addressing mooring design within the CCD literature and highlights a clear research gap. The lack of breadth of control philosophies in published WEC mooring CCD studies also introduces significant uncertainty regarding how sensitive a WEC mooring CCD solution may be to the employed control philosophy. It is noted that, particularly in the case of WEC geometry [80] and array layout [23], radically different CCD solutions emerge for different employed control philosophies.

4.3. WEC mooring systems

Generally, the primary purpose of a mooring, or foundation, system is to provide offshore equipment with reliable station-keeping capabilities, ensuring sufficient resistance against environmental loading, impact, and operational procedures. However, in wave energy systems, mooring systems may serve additional functions beyond station-keeping. For instance, the mooring system can be integrated with the PTO system, contributing to energy capture [81]. In comparison to other offshore applications, WEC mooring systems exhibit several key differences. These include the requirement to function effectively within the wave-frequency (WF) range to facilitate power absorption [33], the presence of significant tidal height variations at nearshore sites and the need to

¹ For more details about these control structures, readers are referred to [11].

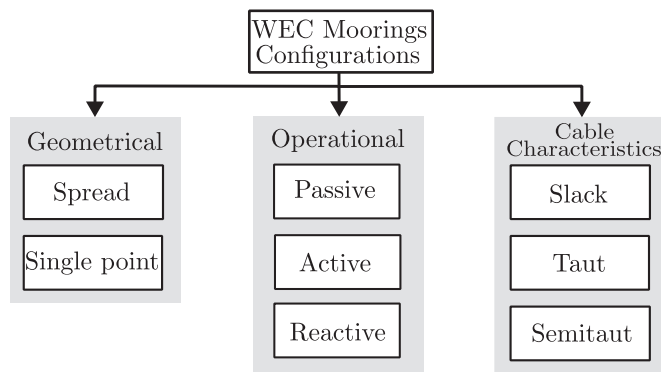


Fig. 9. WEC moorings configurations.

compensate for these [33], the influence of drift forces induced by wave power absorption [82], and the potential impact of connected power cables on device dynamics [83].

4.3.1. WEC moorings configurations

As noted in Section 3, a WEC mooring system, like that of any other moored marine structure, typically comprises three main components: mooring lines, anchors, and connectors. The mooring lines, constructed from various materials, are responsible for transmitting loads between the floater and the anchors, while the anchors provide fixed attachment points on the seabed and the necessary holding capacity to resist mooring loads. Fig. 9 presents a classification of WEC mooring configurations based on three commonly used criteria in the literature [14,84]: geometrical arrangement, operational role, and cable characteristics. It should be emphasised that these categories differ from the *mooring requirements* of a WEC, which stem from device-specific characteristics, as discussed in Section 3. In this section, the various mooring configurations are reviewed with the aim of identifying key mooring design parameters relevant to WEC mooring CCD applications.

From a **geometric** perspective, mooring systems are typically divided into two types: (i) *single point mooring*, where a single connection point allows the WEC to weathervane, providing increased freedom of movement, particularly advantageous for directional WECs (see, e.g., Fig. 10(a),(c)); and (ii) *spread mooring*, where multiple mooring lines are connected to the WEC (see Fig. 10(b),(d)), offering increased positional stability and redundancy in the event of line failure, albeit with more constrained motion.

In terms of **cable characteristics**, mooring systems can be categorised as: (i) *slack* (or catenary) moorings (Fig. 10(c),(d)), where the cables hang loose in a slack; (ii) *taut* moorings (Fig. 10(a),(b)), where the cables are tightly stretched between the WEC and anchors, offering more vertical compliance and typically requiring less seabed footprint [31]; and (iii) *semitaut* moorings, which combine the elements of both taut and slack configurations.

Finally, mooring systems can also be classified based on their **operational role**: (i) *passive* moorings serve only the station-keeping purpose without contributing to energy capture; (ii) *active* moorings, while still primarily serving station-keeping purposes, influence the energy capture process through dynamic interaction with the WEC; and (iii) *reactive* moorings, which go further, forming an integral part of the PTO system and directly participating in energy conversion. This operational classification framework is useful in the context of WEC CCD, where control strategies may influence, or be influenced by, specific mooring configurations and their associated dynamic behaviour. Note that a single geometric configuration, such as single anchor leg mooring (SALM) in Fig. 10(e), can function in any of these operational (passive, active or reactive) roles depending on the broader system context, as shown in [85].

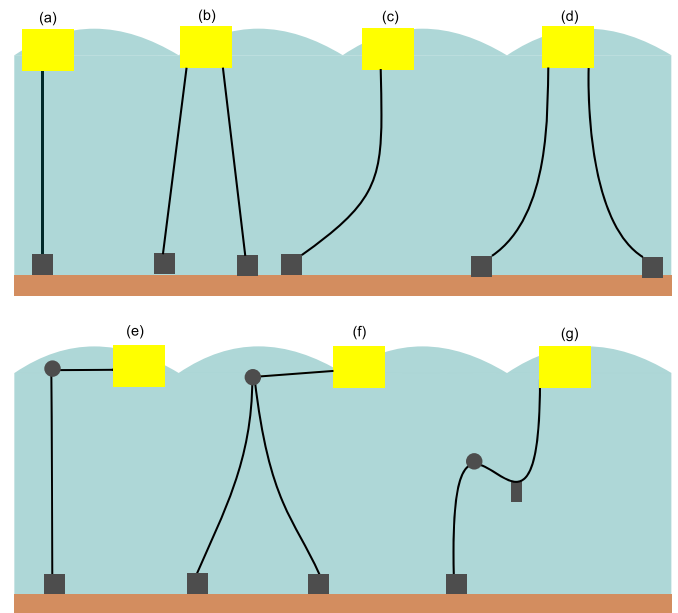


Fig. 10. A subset of WEC mooring types. (a) Taut; (b) Taut spread; (c) Catenary; (d) Multi-catenary; (e) Single anchor leg mooring (SALM); (f) Catenary anchor leg mooring (CALM); and (g) Lazy-S. Adapted from [16].

There are many sub-types of WEC mooring systems that have been explored within the wave energy literature and reviewed extensively in [14,84,86]. A subset of some of the most commonly used sub-types is illustrated in Fig. 10. It is worth noting that certain mooring types are more accessible, or suitable, for wave energy applications than others. For example, single point mooring systems are often recommended for large-dimensioned WECs, with the SALM configuration typically considered the favoured choice [84]. Conversely, for smaller WECs, spread mooring configurations, such as the catenary anchor leg mooring (CALM), are more prevalent in the literature [84]. In addition, more exotic configurations, such as so-called ‘hybrid’ mooring systems [87], which incorporate clump weights and buoys, e.g., the Lazy-S configuration shown in Fig. 10(g), have also been utilised for wave energy systems [84].

From a CCD perspective, two complementary design *philosophies* can be identified for WEC mooring systems. These philosophies determine the choice of design parameters, ρ in (1), within a mooring CCD framework:

- ▷ **WEC mooring configuration parameter CCD:** In this approach, the design parameters primarily define the overall mooring configuration. Typical examples include fairlead positions and the mooring footprint radius. The appropriate choice of configuration-level design parameters depends on the specific mooring requirements of the WEC, and the characteristics of the operational environment. In conventional mooring design (i.e., without CCD), researchers and practitioners typically select a configuration manually, and subsequently optimise mooring line parameters [88]. This sequential process can lead to suboptimal designs and introduces a strong dependence on designer expertise.
- ▷ **WEC mooring line parameter CCD:** In this philosophy, the design parameters are associated with the properties of the mooring lines within a pre-selected configuration. Once a particular mooring configuration has been specified, the corresponding design parameters, ρ in (1), are directly determined. For instance, a relatively simple single-point taut mooring system (Fig. 10(a)) may only require basic line properties, such as line diameter and pretension, as design parameters. In contrast, more complex arrangements, such

Table 3
Illustrative design parameters for the two proposed WEC mooring CCD philosophies.

CCD philosophy	Potential design parameters	Description
Mooring configuration CCD	- Number of mooring lines, - fairlead positions, - line orientation (angle), - anchor / mooring footprint radius, - target line pretension levels	Parameters that primarily determine the global mooring layout and geometric configuration, and thereby influence the overall system dynamics
Mooring line parameters CCD	- line diameter, - line material / construction, - (axial) line stiffness, - line segment lengths, - minimum breaking load, - clump weight properties (mass, location), - buoyancy element properties (e.g., diameter, mass, location)	Physical and mechanical properties of the mooring lines and auxiliary components that can be tuned within a given configuration

as the Lazy-S configuration shown in Fig. 10(g), require additional design parameters associated with auxiliary components, including clump weights and buoyancy elements (e.g., their dimensions, masses, and placement). It is also worth noting that not all mooring configurations necessarily warrant a dedicated WEC mooring CCD exercise, since the coupling between the WEC control system and the mooring response may be weaker in some configurations (e.g., purely passive systems) than in others (e.g., active or reactive).

Table 3 summarises illustrative design variables associated with the two mooring CCD philosophies introduced above. The *mooring configuration CCD* category groups parameters that govern the global layout and geometry of the system, such as the number of mooring lines, fairlead positions, line headings, anchor or footprint radius, and target pretension. These variables primarily determine the overall hydrodynamic and structural response. In contrast, the *mooring line parameter CCD* category contains tunable component-level properties within a selected configuration, including line diameter, material and construction type, axial stiffness, segment lengths, minimum breaking load, and the characteristics and placement of clump weights or buoyancy elements.

It is important to note that, in practice, the distinction between these categories is not always preserved. For example, in [89], multiple mooring solutions for floating WECs are optimised, albeit not within a CCD framework, using design variables drawn from both groups, such as the number of lines (a configuration variable) and buoy dimensions (a line-level variable). Consequently, either category, or an appropriate combination of both, may be treated as plant design variables within a WEC mooring CCD framework.

Another important aspect concerns the structural and operational limits (part of $\mathcal{C}$ in (1)) that constrain admissible system behaviour [14,90]. At the configuration level, these limits include, for example, the maximum platform offset, allowable fairlead and line orientation angles, and restrictions on the mooring footprint. At the line level, constraints typically bound component demands, such as the maximum line tension relative to the minimum breaking load, the minimum allowable bend radius, and required clearances from the seabed and neighbouring structures. Such constraints are essential to ensure that the mooring system operates within safe margins and satisfies reliability requirements throughout the design life. In short, the choice of mooring configuration determines not only which design variables are included in CCD, but also which physical constraints must be enforced within the CCD framework.

Beyond operational constraints, fatigue and long-term reliability are also important considerations in WEC mooring CCD. Control strategies aimed solely at maximising energy capture may increase WEC motion and dynamic mooring loads, potentially accelerating fatigue damage accumulation and reducing component lifetime. Consequently, reliability-related metrics, such as fatigue damage, probability of failure, and mooring lifetime, may be incorporated either as CCD objective functions and constraints, or within the control objective itself through *health-aware* control formulations [91,92]. Such considerations enable a more balanced trade-off between energy production, operational expenditure, and long-term structural integrity.

4.3.2. Mathematical models for WEC mooring systems

Appropriate modelling of WEC mooring dynamics is crucial for optimal mooring system design. This is because physical mooring designs do not always scale predictably, and physical testing can be both costly and time-consuming. More importantly, the mooring system itself can significantly influence overall WEC behaviour. From a CCD perspective, the inclusion of a representative mooring dynamics model within the CCD optimisation process is essential, since the level of model fidelity can directly impact the resulting optimised design. In general, mathematical models for mooring systems articulate the relationship between three main aspects: mooring system parameters (e.g., line diameter, pretension), environmental loads (e.g., wind, current, and wave forces), and physical effects (e.g., buoyancy, weight, and inertia). The specifics of these aspects are not detailed here, as they are well documented in the existing literature [16,93].

Typically, WEC mooring mathematical models can be categorised, based on their complexity, as follows [16]:

- ▷ **Static models:** These assume that the mooring system is in equilibrium under constant environmental loading, neglecting inertial and dynamic effects. They are computationally efficient and suitable for preliminary design but cannot capture dynamic WEC-mooring interactions. A static analysis is typically used to obtain an initial configuration for dynamic analysis.
- ▷ **Quasi-static models:** Quasi-static models assume a uniform and linear transition of the mooring system between two static equilibrium positions over each time-step. Like static models, they neglect hydrodynamic and inertial forces acting on the mooring lines, which can be important for capturing the dynamic response of WECs. In offshore applications, particularly within the oil and gas industry, quasi-static models are widely adopted and are even accepted in some design standards [93], since the primary role of mooring systems in such contexts is station-keeping, and the designs typically avoid excitation in the WF range. However, in wave energy applications, the use of quasi-static models is generally not recommended, except under specific conditions such as fatigue analysis [16] or for very large WEC structures. This is primarily because wave energy systems typically require significant motion (especially under controlled conditions) in the WF range, and many WEC devices are relatively small and dynamically sensitive.
- ▷ **Time-domain dynamic models:** In the time-domain, the dynamic behaviour of a mooring system can generally be described using Newton's second law [93] as:

$$\mathcal{M}_c \mathbf{a} = \mathbf{F}_T + \mathbf{F}_B + \mathbf{F}_r + \mathbf{F}_H + \mathbf{F}_C, \quad (14)$$

where $\mathcal{M}_c$ denotes the mass of the mooring cable, and $\mathbf{a}$ is the acceleration vector. The terms $\mathbf{F}_T$, $\mathbf{F}_B$, $\mathbf{F}_r$, $\mathbf{F}_H$, and $\mathbf{F}_C$ represent forces arising from axial tension, bending moments, torsional moments, hydrodynamic loading, and contact forces, respectively. Solving (14) is not straightforward, and is generally solved either by linearisation or by numerical approximation. In numerical approximation, spatial discretisation is first applied, using methods such as finite elements [94], lumped mass [95], finite differences [96], Galerkin, or

discontinuous Galerkin methods [97], to formulate the system dynamics into a set of ordinary differential equations (ODEs), which are then discretised in time and solved by an integration algorithm. Time-domain dynamic models incorporate dynamic effects including mass, damping, and inertia, enabling time-domain simulation of mooring line responses in various sea states. Although potentially computationally demanding, they are necessary for accurate analysis of WEC-mooring interactions and performance assessment.

Other models are also available from the literature including:

- ▷ **Frequency-domain (linear) models:** Frequency-domain (FD) models are typically faster to evaluate compared to time-domain dynamic models, as they are usually derived through linearisation of the underlying (true) nonlinear governing equations. This speed, however, comes at the cost of reduced accuracy. Several computationally efficient FD mooring models are available in the literature, employing different linearisation techniques [98,99]. Although they are attractive from a computational standpoint, the inherent linear assumptions in FD models prevent them from capturing the nonlinear behaviour of mooring dynamics [16].
- ▷ **Data-based models:** These models are constructed from experimental or high-fidelity simulation data, typically using SysID techniques. Once the high-fidelity model, or scale wave tank, is run to generate training data, the resulting data-based model, whether linear or nonlinear, can be used to estimate mooring system response at a significantly reduced computational cost. As such, data-based models strike a balance between the computational burden of time-domain models and the limited accuracy of linear FD models. These models are gaining popularity in optimisation contexts, although their performance heavily relies on the quality and quantity of training data to ensure robustness and generalisability. Examples of stand-alone data-based mooring models for WECs can be found in [96], while coupled mooring-WEC dynamics using a data-based approach is presented in [15].

Implications for WEC mooring CCD. Regarding the use of mooring dynamics in a WEC CCD framework, both WEC and mooring models need to be coupled, since they are inherently coupled systems with each dynamic affecting the other. The coupling can be either weak, where WEC and mooring dynamics are separately solved iteratively at each time-step, or strong, where both WEC and mooring dynamics are solved simultaneously [100]. It is worth noting that the choice of coupling approach depends on the type of mooring model used and the corresponding implementation mechanism, such as the utilisation of a dedicated mooring solver. A detailed discussion of CCD implementation tools, including coupling of WEC and mooring dynamics, is presented in Section 5. Data-based models naturally lend themselves to strong coupling, as one or both subsystems (WEC and mooring) can be embedded within a unified representation of the complete moored WEC system.

4.4. Objective functions

As mentioned in Section 2.1, the objective function represents a performance metric that a CCD framework aims to optimise. Ideally, the most appropriate performance function for a CCD problem is the LCoE, as defined in (7), since the ‘fuel’ is free and the emphasis is on the cost of conversion. However, implementing LCoE directly within a CCD framework presents several challenges. These challenges include the inherent uncertainty in evaluating OpEx, as well as the fact that LCoE is calculated over the full device lifetime. As a result, various *surrogate* LCoE measures have been adopted in the WEC CCD literature, depending on the specific application. Examples include the κ -factor in [74] and the LCoE* metric in [101].

LCoE (typically expressed in €/kWh or €/MWh) captures both *technical* performance, in terms of energy production (MWh), and *economic* performance, in terms of costs (€). Ideally, a CCD performance function should encompass both technical and economic indicators that are

sensitive to the chosen design parameters, in order to reflect the core objectives of the design process. A detailed discussion on such considerations in selecting an appropriate WEC CCD performance function is provided in [20]. In the WEC mooring CCD literature, a range of objective functions has been employed, as outlined below:

- ▷ **Productivity [25]:** A purely technical performance function, typically expressed in [MWh/y], representing the annual energy production.
- ▷ **Average electric power, $\bar{P}_e$ [102]:** Another purely technical metric, expressed in [kW], which quantifies the average electrical power output over time.
- ▷ **LCoE* [103,104]:** A surrogate measure of LCoE, expressed in [€/MWh], designed to account for both technical and economic performance. LCoE* serves as a computationally tractable proxy for full LCoE, particularly useful within CCD optimisation frameworks.

In [25], the design parameter under consideration is the orientation of mooring lines within a WEC mooring CCD framework. In this context, the use of productivity as the performance function is appropriate, since the optimised design, i.e., mooring line orientation, does not influence the overall cost of the mooring system. However, if the design parameters include cost-sensitive variables, such as cable length or diameter, then employing a techno-economic metric, such as LCoE* [103,104], becomes essential. Given that the WEC CCD domain is still emerging, with mooring system optimisation being among the least explored aspects, there remains significant potential for the development of *new* techno-economic objective functions tailored to such applications. Furthermore, it is worth noting that performance metrics from related domains, such as wind energy, may be transferable to WEC CCD problems. For instance, the author of [105] introduces LCoE *isolines* within a new metric space for wind and hydrokinetic energy systems, an approach that could inspire similar formulations in wave energy system design.

It is important to note that the objective functions discussed above are primarily oriented towards operational performance, such as energy capture and technical productivity. In contrast, the design of mooring systems is often governed by extreme limit states and survival requirements, rather than by operational power states. To the best of the authors’ knowledge, current WEC mooring CCD studies do not integrate control-informed survival strategies, such as active damping or load shedding under extreme sea states, into the optimisation process. Consequently, future objective functions (both design and control) and constraint formulations for WEC mooring CCD should explicitly account for survival and reliability, for example, by including fatigue damage accumulation, probability of failure, or extreme-load metrics as objectives and/or constraints. This would better reflect the safety-critical role of the mooring system and help reduce WEC LCoE by improving component lifetime and reducing failure risk.

The choice of optimisation algorithm for WEC mooring CCD should be problem-driven and depends on the characteristics of the objective function, constraints, and design variables. Gradient-based methods can be computationally efficient for smooth, differentiable problems, but may struggle with non-convexity and discrete design variables. Derivative-free methods, such as genetic algorithms (GA) [106] and particle swarm optimisation (PSO) [107], are generally more robust for non-convex and mixed-integer optimisation problems, although they typically require a larger number of function evaluations. Despite their computational cost, GA-based approaches have been applied in several WEC CCD studies, including mooring optimisation [25] and geometry optimisation [108]. Bayesian optimisation [109], which has been applied to WEC array optimisation [110], can be particularly attractive when objective function evaluations are expensive; however, its effectiveness may decrease as the dimensionality of the design space increases. Consequently, no single optimisation algorithm can be considered universally superior, and the most appropriate choice depends on the specific CCD problem under consideration. For comprehensive

treatments of optimisation theory and algorithms, readers are referred to [111–113], while a short review of optimisation algorithms applied across different WEC CCD aspects is provided in [20].

5. Software tools

This section outlines the simulation requirements, reviews available simulation tools, and describes the implementation framework necessary for WEC CCD mooring optimisation. A detailed screening of various tools suitable for WEC mooring CCD implementation is provided in [114] and is briefly discussed here.

5.1. Simulation requirements

Before reviewing available tools for WEC mooring CCD, it is necessary to define the simulation requirements. A suitable solution must be able to simulate both WEC and mooring dynamics, handle constrained optimisation, and implement advanced control, though tools for optimisation and control often differ from those for mooring simulation. In order to provide a realistic platform for WEC mooring CCD, all simulation components must be relatively time efficient, since repeated simulation runs within an iterative optimiser are required. Nevertheless, CCD is an offline calculation, and high-performance computing facilities may be employed.

To this end, simulation tools for executing WEC mooring CCD are classified into two groups:

► **Group 1 (G1):** Programming languages, and software environments, primarily used for implementing optimisation and control. Examples include MATLAB [115], PYTHON [116], JULIA [117], and WOLFRAM MATHEMATICA [118].

► **Group 2 (G2):** Mooring solvers, specifically developed for detailed mooring system simulation. For example,

- *Commercial tools:* AQWA [119], FLEXCOM [120], MOSES [121], ORCAFLEX [122], PROTEUS DS [123], SEAFEM [124], DEEPC [125], SIMA [126], RIFLEX [127], SIMO [128], and MIMOSA [129].
- *Open-source tools:*, MOODY [130], MOORDYN [131] and MAP++ [132].

It is important to note that WEC dynamics can be simulated in both G1 and G2 environments, with some restrictions on the level of WEC simulation detail available in G2.

5.2. A survey of simulation tools

To evaluate simulation tools for WEC CCD mooring optimisation, a two-level comparison is adopted. First, G1 and G2 tools are assessed separately using defined criteria; then, combinations of G1 and G2 are examined for CCD implementation. For G1 tools, scores on the evaluation criteria (scored 0–5) are detailed in Table 4. The scores are based on the criteria defined in Table 4 and combine information from software documentation, published literature, and expert assessment. Scores range from 0 to 5, where 0 represents very limited capability with respect to a given criterion and 5 represents the strongest capability among the tools considered. Intermediate scores reflect relative performance, while half-point increments (e.g., 3.5) are used when a tool falls between two qualitative levels. The scoring scale is interpreted as follows: 0 = not available; 1 = very limited capability; 2 = limited capability; 3 = moderate capability; 4 = strong capability; and 5 = extensive capability. Note that these scores are intended to indicate relative suitability for the specific WEC mooring CCD context, rather than to provide an absolute ranking of the tools.

Table 5 compares G1 tools across the selected criteria. Overall, PYTHON and JULIA outperform MATLAB and MATHEMATICA, though each tool excels in different areas. Open-source PYTHON and JULIA lead in accessibility, while MATLAB ranks highest for optimisation and control support due to the availability of associated extensive toolboxes. PYTHON follows closely with strong third-party libraries, and JULIA ranks third with its growing ecosystem. MATHEMATICA scores lowest

Table 4

Evaluation criteria for G1 tools (score range: 0–5).

Criterion	Scoring guideline
Accessibility	Open-source tools score highest (5), commercial tools with strict licences score lower.
Speed	Reflects computational efficiency; highly optimised tools score highest.
Backward compatibility	Reflects the ability to maintain compatibility across software versions; stronger compatibility scores higher.
Technical support	Reflects the availability of built-in functionality, documentation, community support, and third-party packages relevant to optimisation and control; stronger support scores higher.

Table 5

Group 1 tools comparison [114]. Aty: accessibility, BC: backward compatibility, TS: technical support.

Tool	Aty	Speed	BC	TS	Total score
MATLAB [115]	2	3.5	2	5	12.5
PYTHON [116]	5	4	4	4	17
JULIA [117]	5	5	4	3	17
MATHEMATICA [118]	2	3	3	2	10

overall but remains superior in symbolic computation, which is not considered a criterion here.

G2 tools (mooring solvers) are evaluated on their handling of mooring dynamics, WEC simulation, accessibility, API integration with G1 tools, and parallel processing; criteria tailored specifically for the WEC mooring CCD optimisation problem. These differ from typical literature comparisons, such as [93], which focus on the comparison of a subset of commercial mooring software, or [133], which examines various DNV SEASAM packages (MIMOSA, SIMO, RIFLEX, SIMA).

Table 6 summarises a comparison of 11 commercial and 3 open-source mooring solvers. From Table 6, it is clear that most mooring solvers are capable of handling nonlinear time-domain mooring dynamics, with the exception of MIMOSA and MAP++. Furthermore, most commercial software packages can simulate WEC dynamics, as they are generally designed as multi-purpose tools, whereas MOODY is the only open-source software that has the capability to simulate WEC dynamics. However, it is worth noting that the level of WEC model fidelity achievable with G2 tools may be restricted by the capabilities of each individual tool. For instance, MOODY can implement the linear Cummins Eq. (6) with nonlinear additives, such as Morison drag and nonlinear Froude–Krylov forces [130]. Another key consideration is the availability of an API, which enables the exchange of data between G1 and G2 tools for WEC mooring CCD implementation. The API should also allow scripting of input files or programmatic modification of design parameters, which is essential for supporting automated iterations within a CCD framework. All three open-source mooring solvers provide API functionality, whereas not all commercial solvers support this capability. It should be noted, however, that some commercial API functionalities are limited to data access, rather than fully coupled simulation, as observed in FLEXCOM. Among API options, PYTHON is the most widely supported programming language. Additionally, the ability to parallelise computations, using multiple CPU or GPU cores, is considered in Table 6. Most commercial software packages offer this capability, while open-source tools generally either lack parallelisation support or provide insufficient information regarding availability.

Finally, Table 7 evaluates different simulation environment combinations for implementing WEC CCD solutions, with a focus on mooring optimisation. Control and optimisation are typically implemented in Group 1 (G1) tools (e.g., MATLAB, PYTHON, JULIA), since Group 2 (G2) mooring solvers generally lack these capabilities. The WEC and mooring dynamics, however, may be implemented in either G1 or G2. Although

Table 6

Group 2 tools (Mooring solvers) comparison [114]. S: static, QS: quasi-static, TD: time domain, FD: frequency domain, Aty: accessibility, Com.: commercial, OS: open source.

Software	Model type				WEC dynamics	Aty.		API facility	Parallel processing
	S	QS	TD	FD		Com.	OS		
AQWA [119]	•	•	•	•	•	•		•	•
FLEXCOM [120]	•	•	•	•	•	•		• ¹	
MOSES [121]	•	•	•	•	•	•			•
ORCAFLEX [122]	•	•	•	•	•	•		• ²	•
PROTEUS DS [123]		•	•	•	•	•			•
SEAFEM [124]		•	•	•	•	•			•
DNV SESAM PACKAGES [134]									
(a) DEEPC [125]	•		•		•	•			•
(b) SIMA [126]			•		•	•		• ³	•
(c) RIFLEX [127]			•		•	•			•
(d) SIMO [128]		•	•		•	•			•
(e) MIMOSA [129]	•	•		•	•	•			•
MOODY [130]			•				•	• ⁴	
MOORDYN [131]			•				•	• ⁵	
MAP++ [132]		•					•	• ⁶	

¹ Only for database access.

² For both PYTHON and MATLAB.

³ Through SIMAPY PYTHON library.

⁴ For OPENFOAM only, PYTHON and MATLAB APIs are still in development.

⁵ For FAST and MATLAB (including SIMULINK and WEC-SIM).

⁶ For PYTHON only.

Table 7

Evaluation of possible combinations of environments to implement a WEC CCD problem for mooring optimisation.

Combination				Evaluation criteria		
Control	Optimisation	WEC model	Mooring system	Ease of implementation	Flexibility	Computational efficiency
G1	G1	G1	G1	Low	High	High
G1	G1	G1	G2	High	High	Medium
G1	G1	G2	G1	Low	Low	Medium
G1	G1	G2	G2	High	Medium	Medium

this makes control and optimisation fixed in G1 across all cases, the evaluation considers all four CCD components, i.e., control, optimisation, WEC dynamics, and mooring dynamics, to capture the integrated nature of co-simulation.

The assessment employs three criteria: ease of implementation, flexibility, and computational efficiency. Ease of implementation is partly subjective, but is considered here under the assumption that users are somewhat familiar with their chosen tools, which is a reasonable expectation, as it is unlikely that a user would select a tool they are entirely unfamiliar with. Based on this framework, the four possible combinations are evaluated as shown in Table 7.

From Table 7, it is worth highlighting the trade-offs across the four combinations. Implementing all components in G1 tools (G1, G1, G1, G1) offers the highest overall computational efficiency by avoiding API overhead, though at the cost of low ease of implementation due to the need for custom mooring modelling. Although G2 tools are typically faster in isolation, (G1, G1, G1, G1) achieves higher overall efficiency by avoiding API communication overhead between G1 and G2 tools. Incorporating a dedicated mooring solver (G1, G1, G1, G2) improves ease of implementation while retaining flexibility, albeit with slightly reduced efficiency. Using G2 solely for the WEC model (G1, G1, G2, G1) performs poorly in both ease of implementation and flexibility, since simulating mooring dynamics in G1 remains inefficient. Finally, employing G2 solvers for both WEC and mooring (G1, G1, G2, G2) provides a good balance between ease of implementation and flexibility, but introduces medium computational efficiency due to API communication.

From the above discussion, it is clear that combination 2 (G1, G1, G1, G2) and combination 4 (G1, G1, G2, G2) emerge as the most practical options for implementing a WEC CCD solution for mooring

optimisation. Nevertheless, combination 4 (G1, G1, G2, G2) carries a caveat, as its flexibility is limited by the range of WEC models supported within the G2 environment.

While discussing tools for WEC CCD implementation, it is important to mention WECOPTTOOL [135], developed by Sandia National Laboratories in the United States specifically for WEC CCD applications. As an open-access Python-based tool, WECOPTTOOL is particularly attractive for implementation and has already been applied to the optimisation of various CCD aspects, including PTO design [136] and device geometry [137]. However, explicit mooring co-design has not yet been incorporated within the framework. Some mooring-related aspects, such as pretension, have been considered, but only through simplified mooring dynamic models, as demonstrated in [102]. Given its modular and open-source nature, WECOPTTOOL could serve as a strong foundation for extending CCD studies to explicitly include mooring systems.

5.3. Implementation framework

This section outlines a possible framework for WEC CCD mooring optimisation, based on the combinations in Table 7. As an example, Fig. 11 shows the possible two combinations to implement a WEC mooring CCD solution, i.e., combination 2 (G1, G1, G1, G2) and combination 4 (G1, G1, G2, G2). In combination 2, optimisation, control, and WEC dynamics are implemented in G1, while mooring dynamics are implemented in G2. An API manages data exchange and reconciles time-step differences between the two environments, with specific exchange variables depending on the chosen configuration. Furthermore, the volume and type of data exchanged through the API strongly influence the overall performance of the CCD framework. In combination 2, illustrated in Fig. 11(a), the exchanged data include input files for the G2 tool (e.g.,

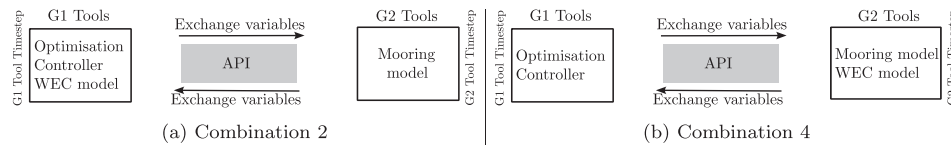


Fig. 11. Possible combinations for implementation framework to solve a WEC mooring CCD optimisation.

mooring attachment points) and output from the G2 tool (e.g., mooring force information) that is passed back to the G1 environment. By contrast, in combination 4, as shown in Fig. 11(b), where both WEC and mooring dynamics are simulated within the G2 tool, the exchange variables differ. Here, control force information is sent from G1 to G2, while the combined WEC–mooring dynamics are returned to G1 to update the control forces for the next iteration.

6. WEC mooring CCD studies in the literature

This section presents a detailed review of the CCD studies focused on mooring optimisation in wave energy literature, while also identifying the research gaps for future research.

6.1. Reported WEC mooring CCD studies

As noted in Section 1, the application of CCD to mooring optimisation for WECs remains largely under-explored, with only four studies identified to date. Table 8 summarises these works, comparing their treatment of key CCD components, including optimisation parameters, objective functions, mooring and WEC modelling approaches, and device types.

In [25], the mooring line orientation, as a design parameter, is optimised within a WEC CCD framework aiming to maximise productivity (performance function). The main contribution of this work lies in the use of a data-based (linear) mooring model derived from numerical data generated using a high-fidelity mooring solver, i.e., ORCAFLEX [122]. The WEC model, in contrast, is a physics-based linear model developed using hydrodynamic coefficients calculated with the BEM software ORCAWAVE. Both WEC and mooring models are then coupled in the same fashion as shown in Fig. 6. A relatively simple, single-frequency PD controller is employed, without the inclusion of physical constraints. It is important to note that [25] considers an *active* three-tether mooring system, meaning the mooring arrangement itself does not directly contribute to energy harvesting; rather, mooring system influence on power absorption arises solely from the dynamic interaction between the WEC and the mooring system. Finally, productivity, a purely technical performance function, is chosen in this paper, since the design parameter (mooring line orientation) does not directly affect mooring system capital costs, although the optimised orientation may have (unquantified) implications for system OpEx.

In [102], the mass-to-line pretension ratio is optimised, using WECOPTOOL [135], for a single-point taut-moored heaving point absorber. The objective function considered is average electrical power, a purely technical objective that does not account for the cost implications of changing the WEC dry mass. Although the WEC dynamics include both the wave absorber hydrodynamics and a PTO loss model, the mooring model is highly simplified, with the mooring force represented as the sum of the PTO force and the air spring pretension force. The use of PS-control, however, allows comprehensive evaluation of control performance, while satisfying a range of constraints. Another limitation of this study is the exclusive use of regular waves, which do not represent realistic sea conditions.

In [103,104], the optimal WEC array layout is determined for various mooring configurations. However, the mooring configurations are not optimised explicitly as separate design parameters in the CCD framework. Rather, the WEC array layout, in terms of inter-device spacing, and array alignment to the incoming wave direction, is optimised for several distinct mooring configurations. The key differences between [103,104] are the array sizes (three and five devices, respectively), the point absorber geometries, and the mooring types (single-point and spread mooring, respectively). An optimal PS-control strategy is implemented to evaluate WEC array control performance, including constraints. A surrogate LCoE performance function, LCoE*, provides a useful trade-off between technical (energy capture) and economic (cost) objectives. A linear WEC hydrodynamic model is used, with a simplified *mass-damper* mooring model.

A comparison of the studies in Table 8 highlights a common focus on point absorbers, which predominantly rely on simplified or surrogate mooring model representations. In addition, the reviewed studies differ significantly in their optimisation objectives, ranging from purely technical metrics, such as productivity and average electrical power, to techno-economic measures, such as LCoE surrogates. Differences are also evident in sea-state representation, with some studies relying exclusively on regular-wave conditions [102], while others use more realistic irregular waves. Similarly, the choice of control strategy also differs across different studies, with some studies using a relatively simplified PD controller [25], while others implement constrained optimal control strategies [103,104] with physical constraint handling. Furthermore, two of the studies, i.e., [103,104], compare different

Table 8

Reported WEC CCD mooring optimisation studies. ρ_{opt} : optimisation parameter(s), Γ : objective function, S: static, QS: quasi-static, TD: time-domain, FD: frequency-domain, DB: data-based, PB: physics-based, PD: proportional derivative, PS-control: pseudospectral control, PA: point absorber.

Ref.	ρ_{opt}	Control strategy	Γ	Mooring model						Mooring type	WEC model		WEC type
				S	QS	TD	FD	DB	Other		PB	DB	
[25]	Line orientation	PD	Productivity							Spread taut mooring	• ¹		PA
[102]	Mass-to-line pretension ratio	PS-control	Avg. electrical power						• ²	Single-point taut	• ³		PA
[103]	Layout and mooring configuration	Passive and PS-control	LCoE*						• ⁴	Single-point slack	• ¹		PA
[104]	Layout and mooring configuration	PS-control	LCoE*						• ⁴	KARRATU	• ¹		PA

¹ Linear hydrodynamics.

² Sum of PTO force and linear pretension force due to buoyancy and gravity.

³ Linear hydrodynamics and PTO model.

⁴ Linear mass-damper model.

mooring configurations, in which the mooring system parameters are not optimised as independent CCD variables; instead, array layout is optimised for each pre-defined mooring configuration. This limits the extent to which the results can be interpreted as true mooring CCD studies.

Overall, the above-mentioned studies demonstrate varied strategies for incorporating mooring considerations into WEC CCD frameworks, ranging from data-based models to highly simplified representations. While each study addresses certain CCD elements effectively, limitations remain in model fidelity, choice of control strategy, parameter scope, and sea-state realism. Notably, all studies, in Table 8, focus on point absorbers, despite other WEC types approaching commercial readiness [10] which could benefit from similar CCD studies. The studies listed in Table 8 rely primarily on numerical modelling. Conducting a full co-design optimisation experimentally is currently prohibitively challenging, as it requires a large number of design iterations that are not feasible in wave-tank testing. In practice, experimental validation is typically limited to the final co-designed solution, or to a subset of representative cases, after numerical optimisation. These observations form the basis for the research gaps identified in the following Section 6.2.

6.2. Research gaps

A critical review of the state-of-the-art reveals that mooring optimisation within a WEC CCD framework remains a highly under-explored research area. Only a limited number of peer-reviewed studies address this integration and, consequently, no comprehensive methodology has yet been established. Moreover, the scope of existing work is notably narrow in terms of device typologies, with most studies focusing on point absorbers despite the increasing commercial readiness of other WEC types, such as floating oscillating water columns (OWCs).

Where mooring systems are incorporated into CCD frameworks, their mathematical models are often oversimplified. For example, the use of linear mass–damper representations in [104], or simple force superposition in [102], neglects key nonlinear and dynamic effects. This limitation is exacerbated by the use of unrealistic environmental conditions, with many studies relying on regular waves, or a limited set of sea states. Such simplified representations fail to capture the complexity of site-specific wave climates, which are essential for informing a robust design optimiser [138].

In addition, the lack of experimental verification of CCD-optimised mooring designs remains a major research gap. This limitation is explicitly acknowledged in the present review, and experimental validation of CCD-optimised mooring systems is identified as an important direction for future research.

Furthermore, most existing studies focus on purely technical objective functions, such as average electrical power, without explicitly incorporating mooring system costs. This omission hinders the ability to evaluate the necessary trade-offs between WEC energy yield and mooring system expenditure. Beyond energy capture and mooring system costs, another important aspect is survival strategies, since mooring design is often governed by extreme limit states, which have not yet been explored within a WEC mooring CCD framework and represent an important research gap. In addition, the influence of alternative control strategies, beyond standard pseudo-spectral methods, remains largely unexplored, limiting understanding of how alternative controllers (e.g., those listed in Table 2) may affect optimal mooring design decisions.

Finally, a significant research gap persists regarding the optimisation of mooring systems, using CCD within WEC array contexts to investigate the potential benefits of shared mooring infrastructure. However, it is important to note that not all WEC types support shared mooring systems, such as single-point bottom-referenced taut-moored devices, e.g., CorPower WEC [38]. While fixed layouts have been compared [103,104], the mooring system parameters themselves have not yet

been treated as optimisable design variables within an array-level WEC mooring CCD framework.

7. Challenges and outlook

Building on the research gaps identified in Section 6.2, the following discussion examines the key technical challenges that currently limit progress and outlines opportunities for future work.

Advancing the field requires overcoming several significant technical challenges, foremost among them the high computational burden of fully coupled, nonlinear, time-domain simulations. When incorporated into iterative CCD optimisation loops, these simulations become prohibitively expensive, thereby limiting the practical resolution of the design space. To alleviate this issue, alternative modelling approaches, such as static, quasi-static, and analytical formulations, are commonly employed in the broader mooring-system optimisation literature [139] and can be similarly integrated into a WEC CCD framework. However, accurate characterisation of mooring-line mechanical properties remains essential, as different line sections (e.g., chain, wire, and synthetic rope) exhibit distinct load–response behaviours that the model must capture reliably. In parallel, future research should prioritise the development of parsimonious surrogate models and model-reduction techniques. Striking an effective balance between model fidelity and computational efficiency will be crucial to enabling the routine use of high-accuracy hydrodynamic and mooring representations within large-scale optimisation studies.

A further challenge lies in the complexity of multi-software coupling. Implementing a WEC mooring CCD solution may require coupling between separate software tools to simulate different components of the CCD framework (see, for example, Fig. 11(a) and (b)). Accurately modelling these couplings presents a significant technical challenge, requiring robust numerical solvers, consistent data exchange between models, and careful handling of numerical stability. While commercial packages like ORCAFLEX [122] offer validated models, their integration into open-source frameworks is often constrained by licensing restrictions. Conversely, open-source tools like MOODY [130] offer extensibility but lack widespread adoption. Overcoming these interoperability issues is essential for the collaborative development of comprehensive design tools. Development of a comprehensive co-simulation platform for WEC mooring CCD optimisation presents an important direction for future research.

In addition, extending single-device frameworks to multi-device arrays introduces additional complexity, regarding hydrodynamic interactions and shared infrastructure. Capturing these effects is computationally demanding, but offers a significant opportunity; treating mooring parameters as optimisation variables in array contexts could unlock potential cost-sharing benefits and improve overall system viability.

Finally, a key challenge lies in formulating techno-economic objective functions tailored specifically to WEC mooring CCD applications, such that the trade-off between economic benefit and system cost is appropriately captured. Therefore, future work must also broaden the scope of CCD frameworks to include diverse WEC/mooring types and explicitly incorporate techno-economic objectives. By integrating CapEx, and ideally OpEx, into performance functions, researchers and designers can move beyond theoretical technical metrics to assess the true commercial feasibility of optimised wave energy systems.

In short, there is considerable potential to reduce wave LCoE through the adoption of WEC mooring CCD strategies, particularly by optimising mooring-system costs, which constitute a major expenditure in both single-device and array deployments. Realising this opportunity, however, will require addressing several significant technical challenges that currently limit the practical implementation of such optimisation approaches.

8. Conclusion

This paper presents a comprehensive overview of WEC CCD for mooring optimisation, addressing both theoretical and implementation aspects. WEC CCD is a rapidly developing research field, with mooring optimisation currently being the least explored area, although this is expected to change in the near future. Nevertheless, moorings comprise a major cost item in any WEC or WEC array deployment. The paper first details the key components of a WEC CCD framework for mooring optimisation, including suitable dynamic models for WEC and mooring systems, control strategies, design parameters, and potential performance functions for evaluation. Then, a new WEC classification is proposed based on the mooring requirements by considering their reference mechanism and directional characteristics. The software tools necessary for implementing a WEC mooring CCD solution are also reviewed, recognising that different elements of WEC mooring CCD solution often require distinct software tools, and potential implementation frameworks are proposed. A critical review of the state-of-the-art highlights both the contributions and limitations of existing studies, providing a balanced overview. The literature reveals that while individual studies address specific aspects of the WEC mooring CCD problem, limitations persist regarding model fidelity, control strategy selection, parameter scope, and sea-state realism. Key technical challenges are identified, including the complexity of multi-software implementations and the high computational cost of coupled simulations and assessment in an array configuration. Finally, future research directions are suggested to help address identified research gaps while effectively managing the associated technical challenges.

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.

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Data availability

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

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