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# Wave energy converter array optimization: A genetic algorithm approach and minimum separation distance study

Chris Sharp, Bryony DuPont*

*Design Engineering Lab, Department of Mechanical Engineering, Oregon State University, Corvallis, OR, USA*

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ABSTRACT

With the need to integrate renewable energy sources into the current energy portfolio and the proximity of power consumers to ocean coastlines, it is important to evaluate marine energy systems, specifically wave energy converters (WECs), as potential solutions for meeting electricity needs. The ability to model these systems computationally is vital to their eventual deployment. The power development, economics, grid integration requirements, operations and maintenance requirements, and ecological impacts must be understood before these devices are physically installed. However, the research area of WEC array optimization is young, and the few available results of previously implemented optimization methods are preliminary. The purpose of this work is to introduce a new WEC array optimization framework to explore systems-level concerns, specifically WEC layout and device spacing. A genetic algorithm approach that utilizes an analytical hydrodynamic model and includes an array cost model is presented, and the resulting optimal layouts for a preliminary test case are discussed. This initial work is integral in providing an understanding of device layout and spacing and is a foundational starting point for subsequent and more advanced WEC array optimization research.

## 1. Introduction

As demand for electricity changes, and as communities seek to continually improve the quality of life and affluence of the growing population, the development and optimization of new, clean energy sources is of paramount importance. Of potential sources, ocean waves have a vast amount of energy and, for the last few decades, research and development regarding the harnessing of this energy has been ongoing. However, the economics of developing, implementing and maintaining wave energy converters (WECs) is lacking – particularly considering sea state volatility over the lifetime of WECs. As the industry moves towards ocean deployment of full-scale grid-connected WECs, an *a priori* optimization of the theoretical power system – including contributing factors such as power development, cost, and system parameters – is required, especially when demonstrating viability to stakeholders.

Current WEC array layout research considers only array power development, resulting in a lack of realism that precludes application of these approaches in deployment situations by offshore energy developers (Fitzgerald and Thomas, 2007; Bellew et al., 2009; Snyder and Moarefdoost, 2014; Ricci et al., 2007; Child and Venugopal, 2010; Child et al., 2011). The primary information missing from current WEC array optimization work is array economics; however, at this early stage of development, there is limited information about the various costs of WEC arrays. Despite this current limitation, it is important that any WEC array optimization framework incorporates cost modeling that can be updated as such information becomes available and accuracy improves.

This article presents a means of finding a WEC array configuration that optimizes conflicting objectives using a genetic algorithm optimization method. First, we will discuss previous approaches that have been used to generate WEC array layouts, followed by a discussion of our developed optimization method (a genetic algorithm approach). Next the objective formulations of cost and power will be presented. Finally, initial results of a preliminary WEC array optimization study using a binary genetic algorithm will be shown involving five devices in a random unidirectional sea state. Since our previous work explores the inclusion of array economics in a binary genetic algorithm (GA) to generate optimal layouts (Sharp and DuPont, 2015a, 2015b), the work presented here further investigates the significance of adjusting the prescribed minimum separation distance on an array's interaction factor as well as comparing the results with those of existing research.

## 2. Previous approaches

Much of the research in WEC array configuration draws upon lessons learned from the wind industry, particularly the effect of a device

* Corresponding author.
*E-mail addresses:* sharpc@oregonstate.edu (C. Sharp), bryony.dupont@oregonstate.edu (B. DuPont).

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on its neighbors. However, unlike wind turbines, where nearby devices negatively affect the power production of surrounding turbines, WEC interactions have the capability to increase the electricity produced by an array (McNatt et al., 2014; Wolgamot et al., 2012). Achieving an interaction factor, $q$, greater than one has been the driving goal of current array optimization work; this demonstrates that array power production is greater than the power produced by the same number of devices acting in isolation (Weller et al., 2010; Borgarino et al., 2011; Goteman et al., 2015). Babarit investigates the interaction factor between single pairs of devices and arrays of devices, noting that while it is possible to achieve positive interaction factors in regular waves, the introduction of irregular waves limits this possibility. The potential for negative interaction between devices in tightly spaced arrays is discussed (Babarit, 2010, 2013). Weller et al. found that positive interaction between devices due to proximity are reduced with increasing significant wave height (Weller et al., 2010). Borgarino et al. suggests that the interaction between devices leads to triangular-shaped arrays achieving a greater value of $q$ than square-based shapes due to masking (Borgarino et al., 2011). Göteman et al. looks at optimizing an array with a large number of devices. They note that arrays are important for limiting power output fluctuation and the clustering of point absorber type devices within an array will help with minimizing energy output variation (Goteman et al., 2015).

Without the use of optimization methods to better account for the factors influencing the configuration of a WEC array, many WEC layouts presented in previous literature have been chosen based on a researcher's educated judgment and then evaluated for power and interaction effects. As an example, Vicente et al. considers several configurations of WECs: single line, hexagonal, triangular, square and offset line (Vicente et al., 2013). Through evaluating these different arrangements and applying waves from different directions, the authors conclude that an increase in the interaction factor will not drive the design of array layouts, but rather factors such as cost and mooring will most influence layout configuration decisions. Additionally, Nambiar et al. utilized empirically-derived variations of radial layouts in the evaluation of cost associated with different electricity transmission options. However, while these works explored cost considerations of WEC arrays, the layouts presented were not explicitly optimized with cost as an objective function (Nambiar et al., 2015).

Introductory research has been conducted utilizing optimization methods for WEC layout design. McGuinness and Thomas implemented an analytical method to optimize the spacing between heave-constrained, spherical point absorbers that are in a line parallel to the oncoming wave (McGuinness and Thomas, 2015). However, it is challenging to include realistic complexities regarding device type and arrangement in a purely analytical method. In later work, they further explored the behavior of three devices in a line perpendicular to the incident wave and show the great variability that can come in power development based on a regular or an irregular sea state (Mcguinness et al., 2017). The initial, primary research used for array optimization comparison was conducted by Child and Venugopal (2010). They have presented two methods for optimizing WEC layouts – each considering five truncated WEC cylinders (similar to Fig. 8) vertically constrained to act in heave. The first method, parabolic intersection (PI), involved placing down-wave devices in the parabolic wake of the up-wave devices. Fig. 1a shows an example array achieved by this method. In addition to the parabolic intersection method, a genetic algorithm approach within MATLAB's Optimization Toolbox was used. This method, limited to 50 generations, achieved configurations such as the layout shown in Fig. 1b (Child and Venugopal, 2010). This baseline work allows for further exploration regarding implementing more advanced optimization techniques in WEC array design.

More recently, Wu et al. demonstrated an improvement in their optimization efficiency when considering a three-tether, submerged buoy array. A variation of an evolutionary algorithm and a covariance matrix adaption-based evolutionary strategy were both utilized. For this specific device type and single frequency, an interaction factor gain was shown that increases the speed of the optimization process (compared to their previous work) (Wu et al., 2016). Sarkar et al. have also completed work in array optimization - specifically of oscillating surge-type devices using machine learning and a genetic algorithm. They state that for these types of devices, clustering should be avoided, but that a positive interaction can be attained between the devices (Sarkar et al., 2016). Ferri considers a covariance matrix adaptation evolutionary strategy (CMA-ES) and a metamodel algorithm (MM) in order to compare computational expense and developed power. The MM is found to be able to converge rapidly, but was not accurate. Though, it could be potentially used as an initial step if paired with a more accurate method in a second phase (Ferri and Cork, 2017). Giassi et al. has also investigated the optimization of a WEC array where the diameter of the device and the gridded spacing of the devices was varied. The results indicate that the changing of a device's diameter primarily affects the cost of a device – not the power development of a device. However, varying the mass has a greater impact on the power developed (Giassi et al., 2017). Bozzi et al. considers annual energy production, hydrodynamic interaction and electrical interaction in connection with array configuration. Assuming a small array, they show that the optimum layouts for their experienced sea states are in the shape of a rhombus or a line (Bozzi et al., 2017).

The referenced work serves as a starting point for WEC array optimization research, and the goal of our current work is to expand the capability of WEC array optimization methods and to increase fidelity of models employed, specifically cost consideration and advanced input parameters. The following sections discuss our novel genetic algorithm approach for finding optimal WEC arrays, and show preliminary results using a similar problem formulation to that of Child and Venugopal (2010).

## 3. Genetic algorithm approach

We used a GA approach because of its ability to efficiently converge on optimal solutions while considering continuous and discrete factors. System optimization with GAs is not a new method; however, the application of such an optimization method in the realm of wave energy converter array design is novel. Additionally, our presented GA was developed specifically to be tuned for this challenge. Applications in the analogous field of wind energy turbine array optimization indicate the need for distinctively implemented algorithms (DuPont and Cagan, 2010). In this section we will give an overview of the workings of our GA – discussing the features that are uniquely important to our problem of optimizing an array of WECs within a binary grid.

To evaluate and compare different possible layouts, an objective function that includes both cost and power is created and utilized. The multi-objective formulation shown in Eq. (1) reflects the trade-off between cost and power as demonstrated by previous research (DuPont and Cagan, 2010; Mosetti et al., 1994; Grady et al., 2005).

$$\text{Objective Function} = \frac{\boldsymbol{Cost}}{\boldsymbol{P}_{20}} \tag{1}$$

In this objective function, the values of $Cost$ and $P_{20}$ represent the cost of and power generated by an array over a 20-year lifetime. Throughout the search, the objective function is minimized and the units are cents per kilowatt. As cost models achieve increased robustness, Eq. (1) could readily represent a lifetime-average cost of energy and could be used for comparing wave energy against sources such as wind or solar. For this specific study, the cost does not impact the layouts due to the simplicity of the cost model and the number of WECs being fixed. Unfortunately, current cost models do not exist that allow for greater fidelity when considering an array of devices. At this current stage of WEC array optimization research, we are considering a scenario that allows for better comparison with previous research – which only considers for a fixed number of devices. Fixing the number of devices allows us to