Programme Area: Marine

Project: PerAWAT

Title: Methodology and site case analysis for the SpecWEC modelling tool

Abstract:

This document describes a methodology for the SpecWEC numerical modelling tool and the application of the methodology to a site case analysis. The methodology is presented as a nine step process, and each step is described in detail. The case analysis describes the application of the methodology to the EMEC wave test site off the coast of the Orkney Islands in Scotland. It includes a sensitivity analysis of the power capture of an array of 100 heaving buoys. The sensitivity of the array power capture to array layout, array spacing, array location, marine current, and variations in sea state parameters were tested. Representative sea states were used for all the sensitivity studies except for the variations in sea state parameters, which were tested using idealized sea states. Although the results are only technically valid for the particular WEC and site modelled, this site case analysis demonstrates that the SpecWEC tool can be used effectively by applying the methodology to assess the impact that different design choices may have on the WEC array power capture and thus support the design of a wave farm in general.

Context:

The Performance Assessment of Wave and Tidal Array Systems (PerAWaT) project, launched in October 2009 with £8m of ETI investment. The project delivered validated, commercial software tools capable of significantly reducing the levels of uncertainty associated with predicting the energy yield of major wave and tidal stream energy arrays. It also produced information that will help reduce commercial risk of future large scale wave and tidal array developments.

Methodology and site case analysis for the SpecWEC modelling tool

WG1 WP2 D6 and D7

DOCUMENT CONTROL SHEET

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Contact	Geraldine Newton-Cross
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CONTENTS

Executive summary

This document contains deliverables WG1 WP2 D6 and WG1 WP2 D7, which consist of a methodology for the SpecWEC numerical modelling tool (D6) and the application of the methodology to a site case analysis (D7). It begins with the methodology, which is presented as a nine step process. Each step is described in detail. The first seven steps consist of parameter choices the user must make for their simulation, such as time step, duration, etc. For each of these choices, the options available to the user are described and suggestions are given about how to make the most appropriate choice. The eighth step of the methodology, creating the mesh for the simulation, is carried out after all of the parameter choices have been made. Finally, a test model run is suggested in the ninth step of the methodology. This step allows the user to verify that the parameter choices they have made are acceptable.

The application of the methodology to the site case follows the step by step description of the methodology. The EMEC wave test site off the coast of the Orkney Islands in Scotland was chosen for the site case analysis. A sensitivity analysis of the power capture of an array of 100 heaving buoys was performed. The sensitivity of the array power capture to array layout, array spacing, array location, marine current, and variations in sea state parameters were tested. Representative sea states were used for all the sensitivity studies except for the variations in sea state parameters, which were tested using idealized sea states.

After the step by step application of the methodology to the site case, the results of the sensitivity analysis are presented and conclusions are drawn. It was found that increasing the number of rows in the WEC array from 3 to 10 decreases the array power capture by about 10%. But, increasing the array spacing from 100 meters to 200 meters increases the array power capture by only 1%. This analysis also showed that variations of location could lead to a difference in array power capture of 5%, although this was primarily due to a change in the incident wave power density. However, inclusion of marine currents only had a very small effect on array power capture, and therefore does not appear significant. It was also found that the variations applied here to the sea state parameters had a very small effect on the array interaction factors. Although the results are only technically valid for the particular WEC and site modelled, this site case analysis demonstrates that the SpecWEC tool can be used effectively by applying the methodology to assess the impact that different design choices may have on the WEC array power capture and thus support the design of a wave farm in general.

1 Introduction

1.1 Scope of this document

The purpose of this document is to outline a methodology for the use of the SpecWEC (Spectral Representation of a Wave Energy Converter) tool, and then apply that methodology to a site case example. This methodology has two goals: to describe the possible choices the user needs to make when using SpecWEC, and to aid the user in making the best possible choices. Following the introduction, Section 2 of this document outlines the methodology (D6) in a step by step fashion. Each choice the user must make before running SpecWEC is described and recommendations are made about the best way to make that choice. In Section 3, the site case example (D7) is presented. The methodology is used to describe the setup of the experiment and the choices required to implement the SpecWEC tool. Finally, in Section 4, conclusions from the sensitivity analysis are drawn and applications and limitations of the methodology are discussed.

1.2 Relationship to other deliverables

These two deliverables consist of the methodology and its application for the SpecWEC modelling tool. This tool was initially developed in WG1 WP2 Deliverables 1 and 2, which described the representation of wave energy converters (WECs) and their implementation in a spectral wave model. WG1 WP2 Deliverable 3 contained the beta software release of the modelling tool, which was validated and verified in WG1 WP2 Deliverables 4 and 5.

1.3 WG1 WP2 D6/7 Acceptance criteria

1. Methodology developed with user group consultation (evidence that invited to input as minimum)
2. Report contains a clear description of the methodology so that it could be understood and followed by a third party
3. Report provides a clear exemplar of how to implement the methodology and results of sensitivity analysis of wave farm configuration
4. Applications and limitations of the methodology will be clearly described

The first acceptance criterion was satisfied with a presentation (QUB-KS-121101) of the draft methodology at the Second PerAWaT User Group Seminar, held on November 7th, 2012 in London. The attendees represented several marine energy institutions. All of the attendees were invited to provide feedback on the presentation of the SpecWEC methodology; however no substantial comments were made at the meeting and there appeared to be general acceptance of the proposed methodology. This is considered as an implicit acceptance of the methodology by the User Group. The second acceptance criterion is satisfied with the description of the methodology found in

Section 2 of this document. The third acceptance criterion is satisfied with the site case analysis found in Section 3 of this document, and Section 4 contains a discussion of the applications and limitations of the methodology, as required by acceptance criterion 4.

2 D6: Methodology

The SpecWEC tool is an add-on for the spectral wave model TOMAWAC that allows for the modelling of arrays of wave energy converters. The tool is primarily designed to be used for the prediction of power output of individual WECs in an array, but could also be used to examine the effect of a WEC array on the surrounding wave climate and coastal processes. Several modifications were made to the TOMAWAC model to produce the SpecWEC tool. These changes allow the user to specify how a WEC is represented in the model and to input their own initial and boundary wave spectra. The following methodology consists of a series of recommended steps for users of the SpecWEC tool. It is designed to walk users through all the decisions they must make in the process of setting up a SpecWEC model run, giving recommendations on how to make the most appropriate choices.

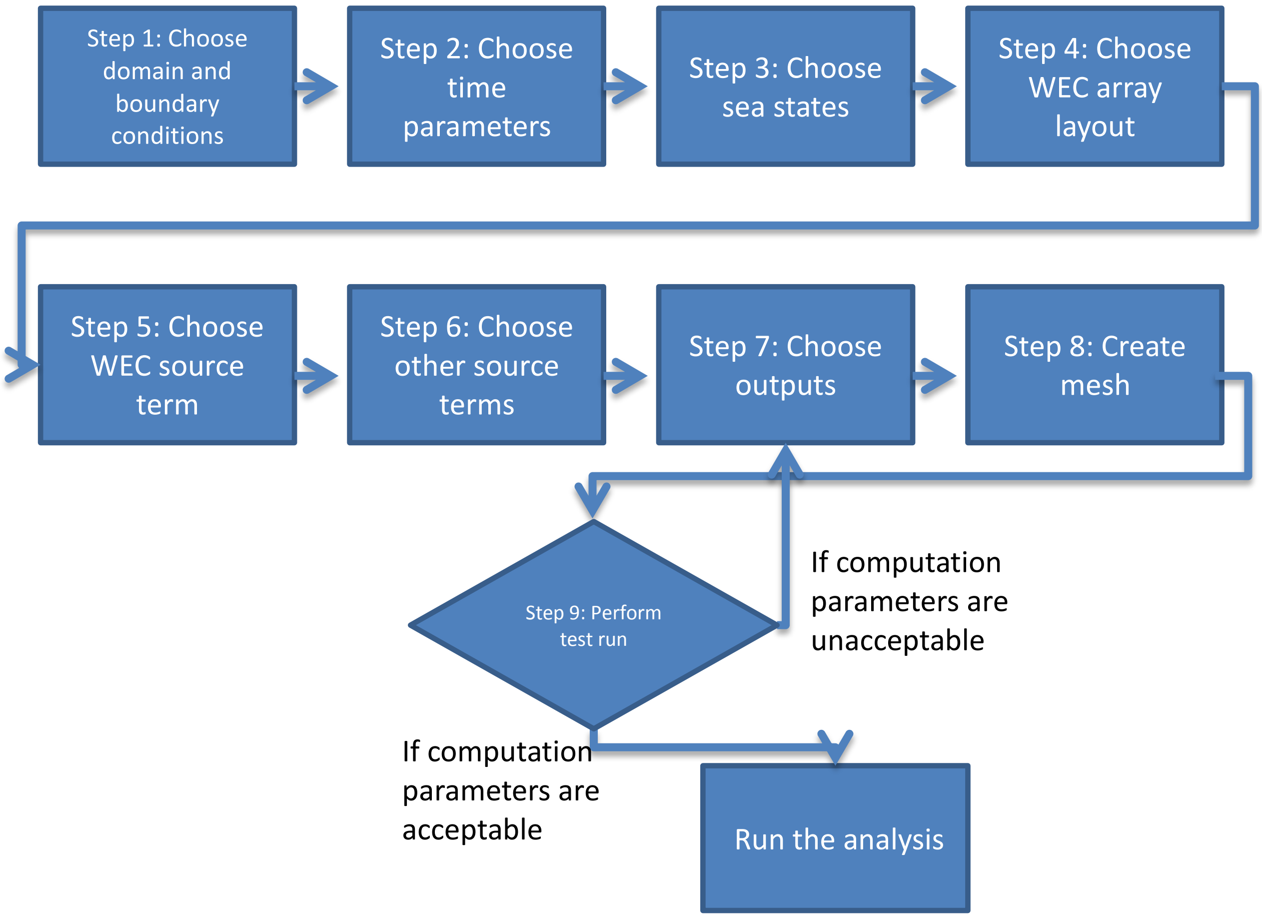
The TOMAWAC model solves for the spatial propagation of the spectrum of ocean waves as a function of frequency and direction. Physical processes such as dissipation due to bottom friction, white capping dissipation, wind generation, and non-linear interactions are parameterized in the TOMAWAC model as sources and sinks of spectral energy. The representation of WECs in TOMAWAC is achieved in a similar manner, with the power absorption and wave radiation due to the presence of the WEC being represented as a sink and source of spectral energy respectively. A full description of the SpecWEC tool can be found in WG1 WP2 deliverables 1 and 2, which describe the representation and implementation of WECs in the spectral wave model TOMAWAC.

There are several input files for the TOMAWAC model that define the mesh, the boundary conditions, and other parameters needed for the model runs. Some of them are described in this methodology, so a full list of them is provided here. The required syntax for most of these files can be found in the TOMAWAC user manual.

1. **Case file** - A text file that lists all the basic parameters needed for a model run, including time step, initial and boundary spectra, duration of run, and number of frequency and direction components. Syntax can be found in the TOMAWAC user manual.
2. **Mesh geometry file** - A binary file that contains the information about nodes and mesh elements. Must be generated in the file format specific to the TELEMAC model system (selafin).

3. **Mesh boundary conditions file** - A text file that contains a list of all the boundary nodes of the mesh and their boundary condition settings. Syntax can be found in the TOMAWAC user manual.
4. **WEC information file** (wecinfo.txt) - A text file specific to SpecWEC that contains information about the WECs including location and any performance coefficients. Syntax can be found in the SpecWEC user report (WG1 WP2 D8 – User manual).

The following diagram illustrates the steps of the methodology. These steps are each described in detail in the following sections. It is recommended that the user first completes all the steps up to and including creating the mesh (Step 8). Once the mesh has been created, the user should perform a test run with the designated mesh, sea states, and time step and model run duration. This will allow the user to make an estimate of how long all of their desired runs will take. If the computation time is considered to be too long, the user may decrease the spatial resolution of the mesh or consider other methods by which the computational time may be made acceptable whilst producing the desired output. It is worth noting that if the spatial resolution of the mesh is decreased, then the time step can be increased. At this point the user can also perform some tests in order to verify that the model run time parameters and WEC inputs are reasonable. The user can iterate this process until suitable parameters are found, and then proceed with their analysis.



2.1 Choose a domain and boundary conditions

The first recommended step for a SpecWEC user is to choose the simulation domain and boundary conditions. There are two different kinds of simulations that may be carried out: a site study using a realistic domain, or an idealized study using most likely a square or rectangular domain. In the case of a realistic domain, an external data set defining both the bathymetry and the positions of the coast and/or any other bounding land masses is required. The size of the domain can theoretically be as large or small as the user requires, although clearly larger domains require greater computational run-time, which is approximately proportional to the number of nodes.

Obviously the domain must at least include the area of interest; however, in addition, the required size of the domain may be affected by the choice of boundary conditions. There are two kinds of boundary conditions available in TOMAWAC; the user may either prescribe a fixed spectrum on the boundary (fixed boundary), or allow energy to propagate through the edge out of the domain without energy coming in (open boundary). Depending on the directional spreading of the incident spectrum used in the simulation, the size of the usable test area of the model domain (i.e. where the wave climate is homogeneous) will vary. Therefore, when choosing the domain it is important to ensure that it extends well beyond the area of interest to avoid distortion of the results due to edge effects.

This effect is illustrated by looking at the results from two simple TOMAWAC model runs. For the two cases, a Jonswap wave spectrum with the same significant wave height and peak period but different directional spreading was propagated through a square domain. One case had very little directional spreading (s = 45), and one case had very large directional spreading (s = 5). The boundary conditions were applied only on the left edge of the square domain. It can be seen in Figure 1 that the usable test area for the WEC array (the region where the significant wave height is equal to 2 metres, the input significant wave height) is larger when the directional spreading is smaller. It is recommended that whenever possible the user deal with this issue by enforcing the fixed boundary condition on all boundaries of the domain. When there is a variable bathymetry, the input spectra may need to vary along the side edges of the domain to replicate the change in waves due to the bathymetry.

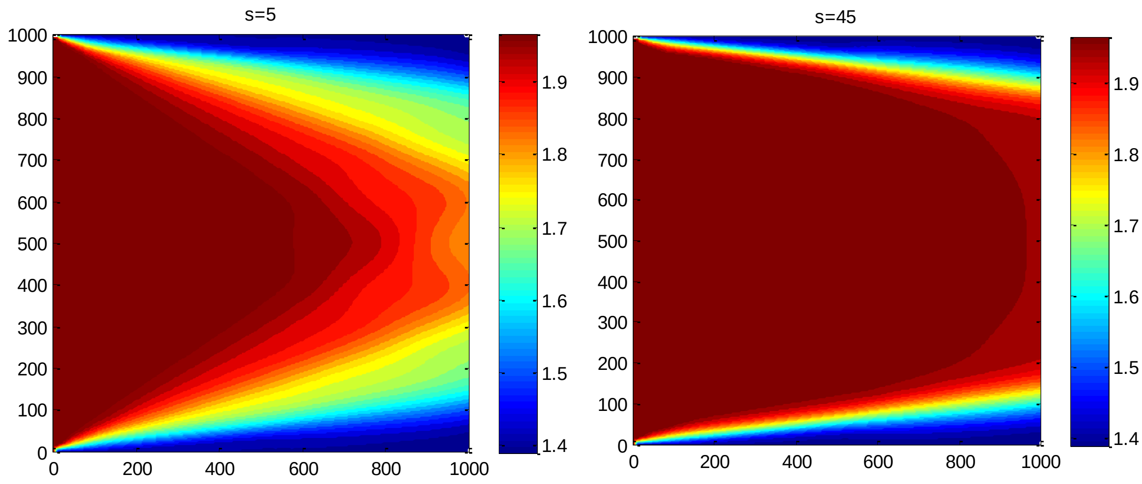


Figure 1: Significant wave height for an incident wave spectrum with directional spreading of s=5 (left panel) and s = 45 (right panel).

2.2 Choose time step and length of simulation

The user must choose a time step and duration for each SpecWEC simulation. One of the advantages of the numerical solving method implemented in the TOMAWAC model is that it is stable at Courant numbers larger than 1. TOMAWAC developers advise that the model can be run up to Courant numbers of 2 (Giovanni Mattarolo, personal communication; TOMAWAC User Manual). This allows the user to use a longer time step for the same grid size than other spectral wave models. Using the computational frequencies for the simulation, the user can calculate the range of Courant numbers and calculate the time step that keeps the maximum Courant number less than 2. The Courant number is calculated as:

$$C = \frac{c_g \Delta t}{\Delta x}$$

where C is the Courant number, c_g is the group speed, Δt is the time step, and Δx is the grid resolution. Given a Courant number no greater than 2, the group speed (which is a function of the computational frequencies being used in the model), and the minimum desired grid resolution of the mesh, the time step can then be solved for.

The ideal length of the simulation depends on the size of the domain. A steady state will be reached when the wave energy with the slowest group speed has propagated completely across the domain. Knowing the group speed and the size of the domain, the user can make an estimate of what the duration of the simulation should be using this simple equation:

$$d = \frac{L}{c_g}$$

Here, d is the duration of the simulation in seconds, L is the length of the domain in the wave propagation direction in metres, and c_g is the minimum group speed in ms^{-1}. This duration can then be divided by the time step length to calculate the number of time steps required for the simulation.

2.3 Designate sea state

Once the user has chosen the time parameters for the simulation, they will need to define the sea state(s) to be used for the simulation. This information is given to the TOMAWAC model in the case file. In the standard TOMAWAC model, only JONSWAP spectra can be designated for initial and boundary conditions in the model domain. These JONSWAP spectra are specified by providing the significant wave height, peak period, directional spreading parameter, and any other information about the spectral shape that the user wishes to modify. The SpecWEC tool has an additional feature where directional frequency spectra can be read in from an input file in text format. This allows the user to set the spectral shape and directional spreading to whatever they choose along the fixed boundaries of the domain. In addition, it is also possible to vary the input spectra along the boundaries of the domain in the TOMAWAC model by modifying the TOMAWAC source code, which then requires recompiling and linking. Details about this feature can be found in the TOMAWAC manual.

2.4 Choose WEC array configuration

After the simulation domain has been chosen, the user must choose the configuration of the WEC array. Because each WEC is represented by a single computational node, the intended grid resolution must be sufficiently fine so that no more than one WEC occupies each node. There is no limit on the number of WECs that can be included. The SpecWEC tool requires the user to specify either the (x,y) position of each WEC or the mesh node number of each WEC. If only the (x,y) position is supplied, then the nearest computational node to that position is used for the WEC location. However, this may lead to the actual WEC positions varying from the designated position by as much as the computation grid resolution, which may be an undesirable. Therefore, it is recommended that the user create the mesh with nodes at the desired WEC locations, to avoid this problem.

2.5 Choose source term representation of WECs

Once the sea states and WEC array configuration have been chosen, the user currently has three options for the representation of their WEC in the SpecWEC tool. Each of the options is for a source term representation of the WEC; that is each WEC is located at a single computational node, and the power absorbed and radiated by the WEC are treated as a source/sink of spectral wave energy. There are two built-in source term representations and a blank template provided for the user to write their own representation. For the two built-in source terms, the user must modify the wecinfo.txt file to include information about the specific WEC they are modelling. The first built-in WEC source term uses a linear transmission coefficient that is frequency dependent. For this simple representation, the user only has to designate the natural frequency of the device being represented (it is unlikely that this source term would be used for a real WEC, but can be useful for more preliminary studies where the WEC is yet to be fully specified). The second built-in WEC source term is a linear point absorber representation. For this source term, the user must provide the frequency dependent added mass, added damping, and exciting force coefficients of the point absorber, as well as the mass of the device, the PTO damping coefficient (for a linear PTO), and the hydrostatic stiffness. The hydrodynamic coefficients can be obtained from WAMIT or from another source by the user prior to use of the SpecWEC tool. The third option is for the user to write their own source term representation as a FORTRAN dynamic link library file (.dll). This allows a user to keep details of their device performance confidential from other users. A blank template of the source term subroutine is provided with the SpecWEC source code. For this option, the user must compile the .dll file and link the TOMAWAC object and library files using a Fortran 90 compiler. Further details can be found in the SpecWEC user report (WG1 WP2 D8 – User manual).

Whilst it is convenient to talk of “the user” in reality it is possible that in any single case there will be many users of SpecWEC with different roles and perspectives. In the majority of cases multiple users is not an issue; however, where there is confidential information on device performance SpecWEC is structured to maintain this confidentiality. For example, a wave farm developer may wish to use SpecWEC to assess the productivity of a particular device, whilst the device developer may not wish to share the source code for the representation of their device since within there could be indications to how the device operates that is considered confidential. In this case the device developer could write an appropriate source term for their device and then compile it into a ‘dll’. The wave farm developer could then use the device source term to assess the performance of the wave farm, but would not have access to the source code that is considered confidential by the device developer.

2.6 Choose other source terms

In addition to the WEC source term, there are other physical mechanisms that can be represented in TOMAWAC as sources and sinks of energy. These include white capping, quadruplet and triad nonlinear interactions, wind input, bathymetric breaking, and bottom dissipation. If the user wishes to isolate the effect of the devices in an array, they may use only the WEC source term and turn all the others off. However, for a more realistic simulation, it is necessary to use include additional source terms. Following the TOMAWAC guidelines, it is recommended that for shallow water depths the bathymetric breaking and triad nonlinear interactions are used, while in medium to deep water depths the white capping, quadruplet nonlinear, and bottom dissipation source terms are used.

2.7 Choose outputs

The user must next choose which outputs are required to assess the results of the simulation. It is possible to output several variables on the 2D mesh in TOMAWAC, including variance, significant wave height, and wave power and many others. The complete list can be found in the TOMAWAC manual. In addition, the directional spectra can be output at any desired (x,y) coordinate. The built-in WEC source term subroutines automatically output the power absorbed as a function of frequency (in both the linear and point absorber subroutine), and the displacement of the device, the radiated power, and the power takeoff coefficient in the point absorber subroutine. The simplified WEC model outputs the discretised absorbed power spectrum from each WEC, whilst the point absorber model also outputs the response spectrum, the spectral energy density of the radiated waves and the variation of the PTO coefficient with frequency (which is useful for understanding non-linear PTO systems). If the user writes their own subroutine they are responsible for outputting the data that they require.

2.8 Create the mesh

The next step in the process of using the SpecWEC tool is to create a mesh for the simulation. There are numerous mesh-generating software programs available for creating an unstructured triangular mesh as required by TOMAWAC. However, TOMAWAC only accepts mesh geometry files that have been saved in a particular binary format. The meshing software program MATISSE is packaged and released along with the TOMAWAC source code, which is capable of saving the mesh files in the required binary format. In addition, BlueKenue (BlueKenue 2013) is an open source program that can used to generate meshes and save them in the correct format. The BlueKenue program can also open meshes from several different mesh generators (such as ArCINFO or ADCirc) and save those meshes in the correct format for the TELEMAC modelling system. TOMAWAC requires both a mesh geometry file that is saved in binary format, and a text file that contains the information about the location and kind of boundary nodes. This boundary condition text file can also be automatically generated using the BlueKenue program.

In order to create the mesh, the user must specify the domain bounds, a target grid resolution, and any desired locations for computational nodes (hard points). It is suggested that the user set the WEC locations as hard points in the mesh. If multiple WEC array configurations are to be tested, the user may wish to designate all the potential WEC locations as mesh hard points to allow for the use of only one mesh, which will facilitate direct comparison between results of all those tests. For large domains, it is useful to make a mesh with variable node density, i.e. one that has a higher node density around the WEC array and near coastlines and rapid changes in bathymetry and less nodes in areas far away from those areas. It is important to remember that the node density must still satisfy the Courant number condition so that the grid resolution should never be less than used to define the time-step length (see Section 2.2). The maximum number of mesh node points that can be used depends entirely on the processor and memory capabilities of the machine that is used for the computation. It is recommended that the user designs a few simple meshes with varying resolution/number of nodes in order to estimate the maximum number of nodes their machine is capable of running.

2.9 Perform a test run

The final step of the process is to run the SpecWEC tool. The required files include the mesh geometry file, the boundary conditions file, any files required for the source term subroutines (e.g. wecinfo.txt for the built-in subroutines), and the steering file that controls the simulation. This test run is used to produce an estimate of the computational time that will be required for all the runs the user wants to do. Additionally, it is recommended to complete some checks on the simulation in order to ensure that the choices made for running the simulation are correct; namely

- Simulation duration
- Time-step length
- WEC characteristics

In order to ensure that the duration of the simulation is adequate, it is useful to examine the time evolution of either the significant wave height or the wave spectrum in the domain. If it is still changing significantly between time steps at the end of the simulation, then the duration is inadequate. If these values have stopped changing a long time before the end of the simulation, then the duration could be shortened.

The acceptability of the time step can also be checked by examining the significant wave height or wave spectrum pattern. Figure 2 shows a simple example for a single WEC located at the centre of a rectangular domain. This model setup was run for two different time steps: 6.5 seconds (top panel) and 0.5 seconds (bottom panel). It can be seen that the energy has skipped between grid points in the top panel, because the time step is too long. However, in the bottom panel with the shorter time step, the interference pattern behind the WEC is continuous, which is the desired effect.

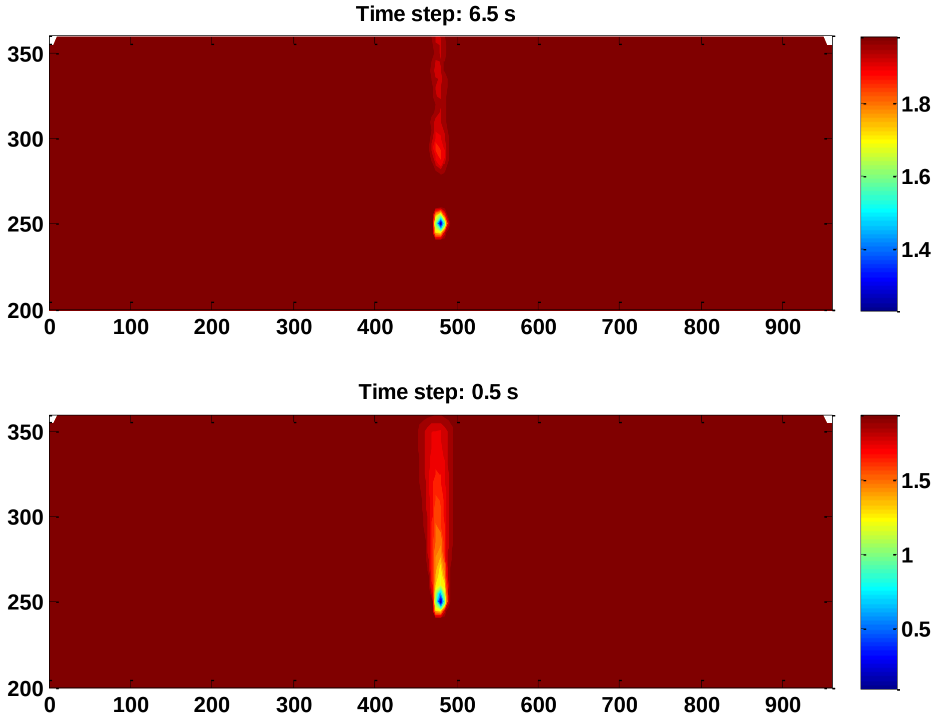


Figure 2: Significant wave height for model run with time step 6.5 seconds (top panel) and 0.5 seconds (bottom panel).

Another check should be carried out on the output relating to the WECs in order to ensure that SpecWEC tool is being used with acceptable parameters. The wave spectrum at the WEC locations should be output and examined to make sure that the device is not taking out more energy in a particular frequency than available in the incident wave, resulting in zero values in the wave spectrum. If this is occurring, then the mesh or WEC parameters will need to be modified so that the energy can be conserved.

If any of the checks yield unacceptable results, then the user should change the model run parameters and run another test run. This should be repeated until the results from the test run are acceptable. Once satisfied that the SpecWEC/TOMAWAC model is running as required the user can proceed and complete their analysis.

3 D7: Site Case Example using the methodology

3.1 Problem description

The site case example was designed to demonstrate how the SpecWEC modelling tool could be used by a device/project developer or a researcher to investigate the sensitivity of the performance of a large array of wave energy devices to a variety of design parameters. The site chosen for this example was the European Marine Energy Centre (EMEC) wave testing area, Figure 3, which is located off the coast of the Orkney Islands in Northern Scotland.

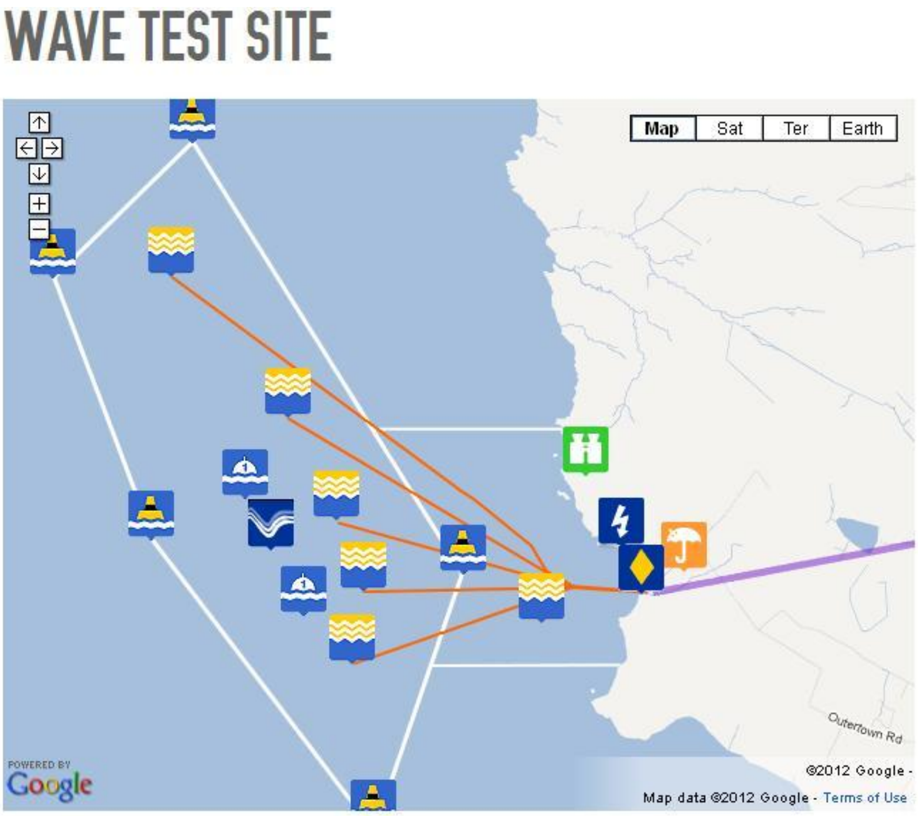


Figure 3: EMEC wave test site. From the EMEC website (www.emec.org.uk)

The SpecWEC modelling tool was used to examine an array consisting of 100 heaving buoy wave energy devices. The sensitivity of the array power capture to different array design parameters such as number of rows in the array, spacing of the array, as well as the location of the array along the coastline and presence of background marine current were tested using representative sea states. Additionally, the sensitivity of the array power capture to sea state parameters such as spectral bandwidth, significant wave height, energy period, directional spreading and peak wave direction was also tested using idealized sea states. Section 3.2 contains a step by step description of how the site case was implemented in SpecWEC by applying the methodology and Section 3.3 contains the results from the site case sensitivity analysis.

3.2 Step 1: Choose a domain and boundary conditions

The first step in the methodology is the choice of the domain and boundary conditions for the site case. Part of the sensitivity analysis involves representative sea states that should be propagated from an offshore boundary over the site bathymetry to the array location. In order to save computational time, a two step process was implemented. First, the representative sea states were propagated to the proposed location of the WEC arrays using a domain covering a large geographic area. This only needs to be done once for each sea state. The resulting full directional frequency wave spectra were saved at the boundary of a smaller grid that contains the different array configurations to be tested. Finally, the sensitivity analysis is performed by applying the saved sea states at the boundaries of the smaller grids.

For this site case analysis, two different locations of the WEC array are analysed; thus three different domains are needed. The first is the large grid that is used to propagate the sea states to the boundaries of the two WEC array locations, and the other two are smaller grids which contain the proposed wave farm locations.

After choosing the domain for a run, the boundary conditions must be determined. For the larger domain, realistic sea states were applied to the north, west, and southern boundaries and the eastern boundary (the coastline) had no applied boundary condition. The eastern boundary had no applied boundary conditions because the waves were propagating to the east, and therefore no waves from that boundary would propagate into the domain. For the smaller domains with the idealised sea-states, the desired sea states were applied to the northern, southern, and western boundaries, and the eastern boundary had no applied boundary condition. The boundary conditions were applied on the northern and southern boundaries of each domain to minimise edge effects. In this case this is considered reasonable since the change in bathymetry is relatively small resulting in a minimal variation in the spectra along the side boundaries. If the spectra were to change significantly along the edges of the domain this should be reflected in the boundary conditions applied.

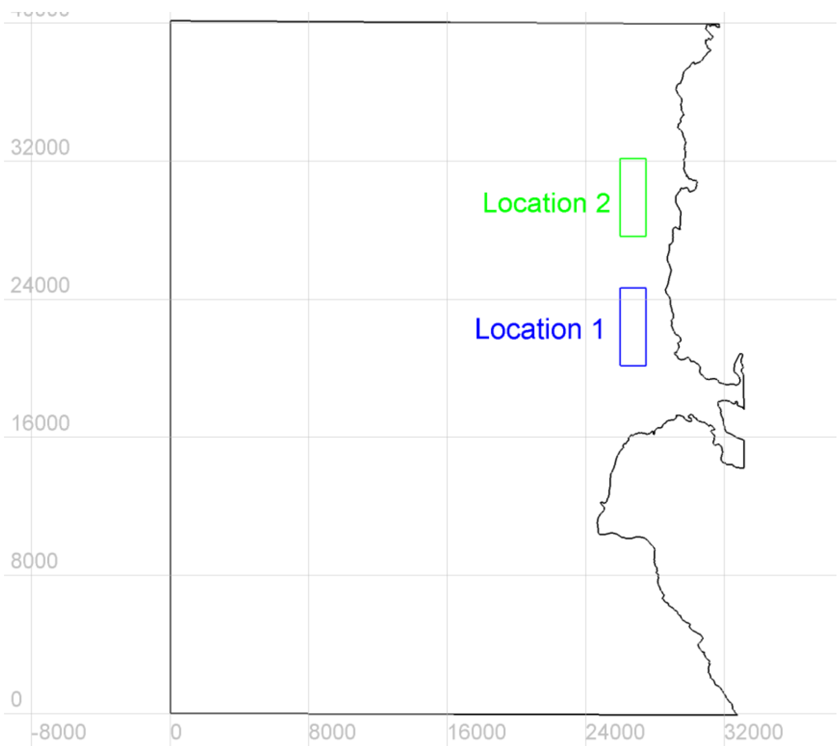


Figure 4: Plot showing the large domain (black line) used for propagation of the initial sea states. Also shown are the smaller grid domains used for the WEC array analysis (Baseline Location 1: blue line and Location 2: green line).

3.3 Step 2: Choose time step and length of simulation

The time step and length of simulations for both the large grid and the smaller ones were chosen using the equations outlined in section 2.2. The large grid had a length of 34 kilometres, and the smallest grid resolution was 100 metres. The smaller grids had a length of 1.5 kilometres and a grid resolution of 25 metres. The fastest group speed for both runs (calculated from the computational frequencies) was 18.8 m/s (based on the lowest frequency component used in the model) and the slowest group speed is 1.56 m/s (based on the highest frequency component used in the model). The time step can be calculated using:

$$\Delta t = \frac{C\Delta x}{c_{gfast}}$$

where C is the Courant number, c_{gfast} is the fastest group speed, Δt is the time step, and Δx is the minimum grid resolution. Here, the fastest group speed is used because this corresponds to the maximum Courant number and thus this equation ensures that the maximum Courant number will be less than 2. Using a maximum Courant number of 2 as recommended by the TOMAWAC developers, the time step for the large grid is calculated as 10 seconds (rounding down to the nearest 1.0 seconds) and for the smaller grid is calculated as 2.6 seconds (rounding down to the nearest 0.1 seconds). The duration of the run can be calculated using:

$$d = \frac{L}{c_{gslow}}$$

where c_{gslow} is the slowest group speed and L is the length of the domain. Using this equation gives a duration of 21,781 seconds (or approximately 2200 time steps) for the large mesh and a duration of 960 seconds (or approximately 400 time steps) for the smaller mesh.

3.4 Step 3: Define sea states

The proposed analysis for this site requires the use of two different sets of sea states. The first set contains sixteen representative sea states, which are used to test the sensitivity of the array power capture to layout, spacing, location, and marine currents. These 16 sea states were derived from data from the EMEC site (Flocard and Finnigan, 2009). Each of these sea states was applied as a Bretschneider spectrum to the north, south, and west boundaries of the larger grid. The main wave direction was east, and the directional spreading parameter was 15.

Table 1: Realistic sea state parameters

Sea-state	Hs (m)	Te (s)	Tp (s)	Freq (%)
1	1.5	7.6	8.8	4.9
2	2.2	10.1	11.7	9.6
3	2.9	7.5	8.7	7.1
4	4.1	8.5	9.9	7.6
5	4.5	9.8	11.4	14.7
6	4.9	11.5	13.3	2.9
7	6.6	11	12.8	1.8
8	4.2	12.6	14.6	1.5
9	0.3	4.5	5.2	4.1
10	0.5	8.3	9.6	3.7
11	1.5	5.8	6.7	6.3
12	1.7	6.8	7.9	18.6
13	1.6	8.1	9.4	11.7
14	2.5	8.9	10.3	3.6
15	2.0	10.9	12.6	1.5
16	3.6	10.2	11.8	0.8
				100.0

These 16 realistic sea states were run on the larger grid, and the directional frequency spectra at points along the boundary of the smaller grid were saved. These output spectra were located 100 metres apart. These spectra were interpolated to a spacing of 25 metres, and then applied to the boundaries of the smaller grids.

In general marine currents are highly complex with structures such as eddies at a number of different spatial scales. To generate this data for the site would require significant additional modelling effort, which may be not justified if the impact of marine currents is found to be minimal.

Consequently, to investigate the sensitivity of the WEC array power capture to marine currents the 16 representative sea-states are modelled both in the absence of marine currents and with a southward marine currents of 0.5 metres/second. This marine current was chosen as a representative current for the EMEC site that in extremis could be encountered at the proposed location, based on the Pentland Firth and Orkney Waters Regional Locational Guidance for Marine Energy produced by the Scottish Government (http://www.scotland.gov.uk/Topics/marine/marineenergy/wave/rlg/pentlandorkney/mspfinal). Note that this sensitivity to marine currents is for array interactions and not the WECs themselves. If the performance of the WEC were sensitive to marine currents then this would need to be included in the WEC source term.

The second set of sea-states contains 6 idealized wave spectra, which are used to analyse sensitivity to sea state parameters. The parameters investigated are spectral bandwidth, significant wave height, energy period, mean direction, and directional spreading.

Table 2: Idealized sea state parameters

Sea-state	Hs (m)	Te (s)	fp (Hz)
1	1.0	7.0	0.123
2	2.0	7.0	0.123
3	2.0	9.0	0.096
4	3.0	9.0	0.096
5	3.0	11.0	0.078
6	4.0	11.0	0.078

For each of these 6 sea states, the sea state parameters were varied as follows:

- Spectral bandwidth: gamma = 3.3, 2.5, 1.5, **(1.0)**
- Peak direction: theta = **(90)**,100,110,120
- Directional spreading: s = 99, 30, **(15)**, 5
- Variation in energy period: dTe = -0.5, -0.25, **(0)**, +0.25, +0.5
- Variation in significant wave height: dHs = -0.5, -0.25, **(0)**, +0.25, +0.5

All of these sea states were applied directly at the boundaries of the small location 1 grid. The baseline settings (those that were held steady while the other parameters were varied) are those values that are in brackets and bold in the above list.

3.5 Step 4: Choose WEC array configuration

In this case study three different types of variation in the WEC array configuration were investigated.

1. Variation in array layout
2. Variation in inter-WEC spacing

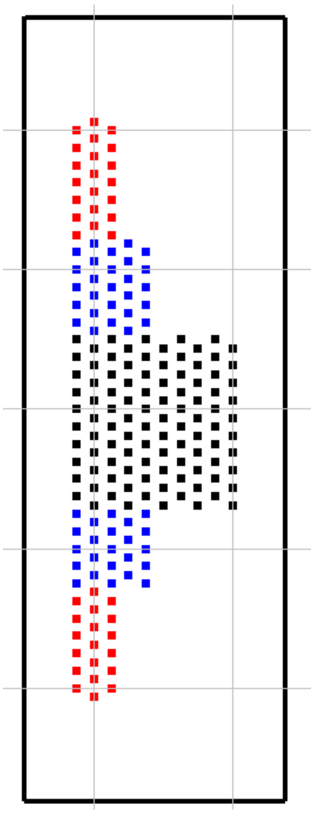
3. Variation in array location

All of the configurations tested included a baseline array layout that consisted of 100 devices in 5 rows spaced 100 metres apart. The WECs in each row are also spaced 100 metres apart and each is staggered by half the separation distance. This configuration was also used for the investigations into the effect of marine currents and the sensitivity to sea-state parameters.

Three different array layouts were modelled. The first consisted of 3 rows of WECs, the second of 5 rows of WECs, and the third of 10 rows of WECs. To keep the number of WECs consistent the number of WECs in each row for each layout were 33/34, 20 and 10 WECs respectively. The WECs in all of the three array layouts were spaced 100 metres apart. These layouts are shown in Figure 5(a).

Three different WEC spacings were also modelled. Each of these arrays consisted of 5 rows of 20 devices. The spacings tested were 100 metres, 150 metres, and 200 metres. These layouts are shown in Figure 5(b).

Two different array locations were modelled. At these locations the arrays consisted of 5 rows of 20 devices. The two locations are illustrated in Figure 4.



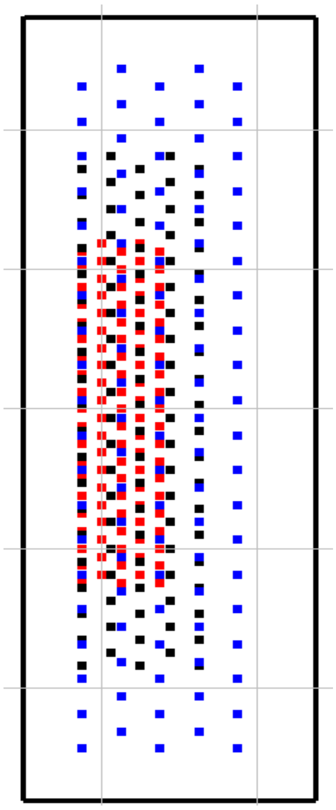


Figure 5: (a) Left panel: Array layout configurations. 3 rows (red), 5 rows (blue), and 10 rows (black). (b) Right panel: Array spacing configurations. 100 metres (red), 150 metres (black), and 200 metres (blue).

3.6 Step 5: Choose source term representations of WECs

The WEC used for the site case study was a heaving point absorber. The source term representation for this type of device is included in base version of SpecWEC. In this representation, certain characteristics of the device must be specified. These include the device mass, hydrostatic stiffness, the added mass, radiation, and exciting forces as a function of frequency, a PTO coefficient and a calibration factor that is associated with the local topology of the grid. The device characteristics used in this study were the same as those used in the previous deliverable WG1 WP2 D4: Comparison of SpecWEC with numerical models. The full scale heaving buoy is represented as a hemispherically-ended cylinder with a radius of 10 metres and a draft of 20 metres. The added mass, radiation, hydrostatic and exciting force coefficients were obtained using the WAMIT potential flow modelling software. A linear damping power take-off coefficient representation with a value of 7.0 MNs/m was applied.

The calibration factor that is associated with the grid represents the area over which wave energy is removed from the incident wave climate, which converts the energy extracted by the WEC to be converted to a reduction in spectral energy density used by TOMAWAC. This calibration factor was determined using an iterative process. Because a regular grid is used (see Step 8) the calibration factor only needed to be determined for one of the WEC locations because it is the same for each computational node in the regular grid used for the array power calculations. The iterative process starts by integrating the energy flux around a single WEC node, which was compared to the power absorbed as calculated by SpecWEC. The area over which energy is taken out was adjusted until the integrated energy flux around the WEC node matched the power absorption by the device, satisfying the divergence theorem. For the small regular grid with 25 metre spacing, the area was found to be 630 m^2. Further details of this calibration procedure can be found in WG1 WP2 D8.

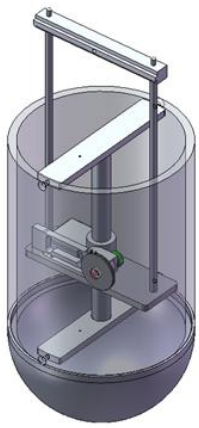


Figure 6: Schematic of the heaving buoy modelled for the site case.

3.7 Step 6: Choose other source terms

In addition to the WEC representation source term, there are several other source terms that can be included in the TOMAWAC model. These represent the physical processes of white-capping, quadruplet wave-wave interactions, triad wave-wave interactions, wind generation, bottom friction dissipation and depth-limited wave breaking. Because the area of interest is in intermediate water depth, the source terms used for this site case study are those recommended by TOMAWAC developers for domains with medium to deep water depth. These are bottom friction dissipation, quadruplet non-linear interactions, and white-capping.

3.8 Step 7: Choose outputs

For each of the model runs, different outputs are available to the user. For the larger grid runs performed for this site case, the directional frequency spectra were output at 100 metre spacing along the boundaries of the smaller grids. Additionally, the significant wave height was output at each point in the domain, to allow verification that the system had reached a steady state. For the runs with the smaller mesh, the power capture as a function of frequency for each wave energy device was output along with the significant wave height and the directional frequency spectra at the locations of the WECs. The significant wave height and directional frequency spectra were chosen as outputs in order to check that the model run parameters are within acceptable bounds as defined in Step 9 of the methodology.

3.9 Step 8: Create the mesh

As stated earlier, three meshes were required for this case study. The first mesh was of the large domain, which was used to propagate the sea state into the array locations as specified in section 3.3. The mesh grid spatial resolution was varied from 400 metres near the western (offshore) boundary to 100 metres at the boundaries of the smaller grids used to assess the WEC array power performance. The north, south, and western boundaries of the smaller grids for the two different locations were set as hard points in this mesh so that the frequency directional spectra at those points could be saved at 100 metre spacing.

The smaller meshes that were used for the model runs including the wave energy devices were designed to have a regular grid, as shown in Figure 7.

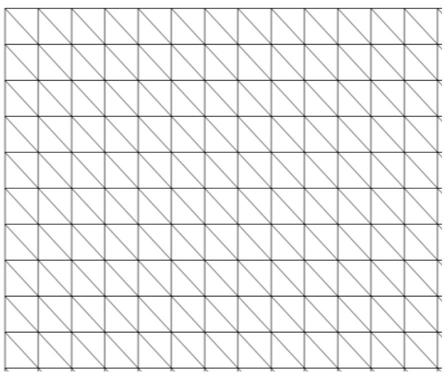


Figure 7: Closeup of the regular grid used for the WEC array performance calculations.

A regular grid was used so that the same calibration factor, which depends on the local grid topology, could be used for all WECs. This significantly reduced the effort required in setting up the model. Both of the smaller meshes had a grid resolution of 25 metres, meaning that there were at least 3 computational nodes between each wave energy device (the smallest spacing for wave energy devices was 100 metres). Because of the characteristics of the regular grid defined, no hard points needed to be created for WEC nodes. The smaller meshes have a depth range of 50 to 70 metres and span 1500 metres in the east-west direction and 4500 metres in the north-south direction.

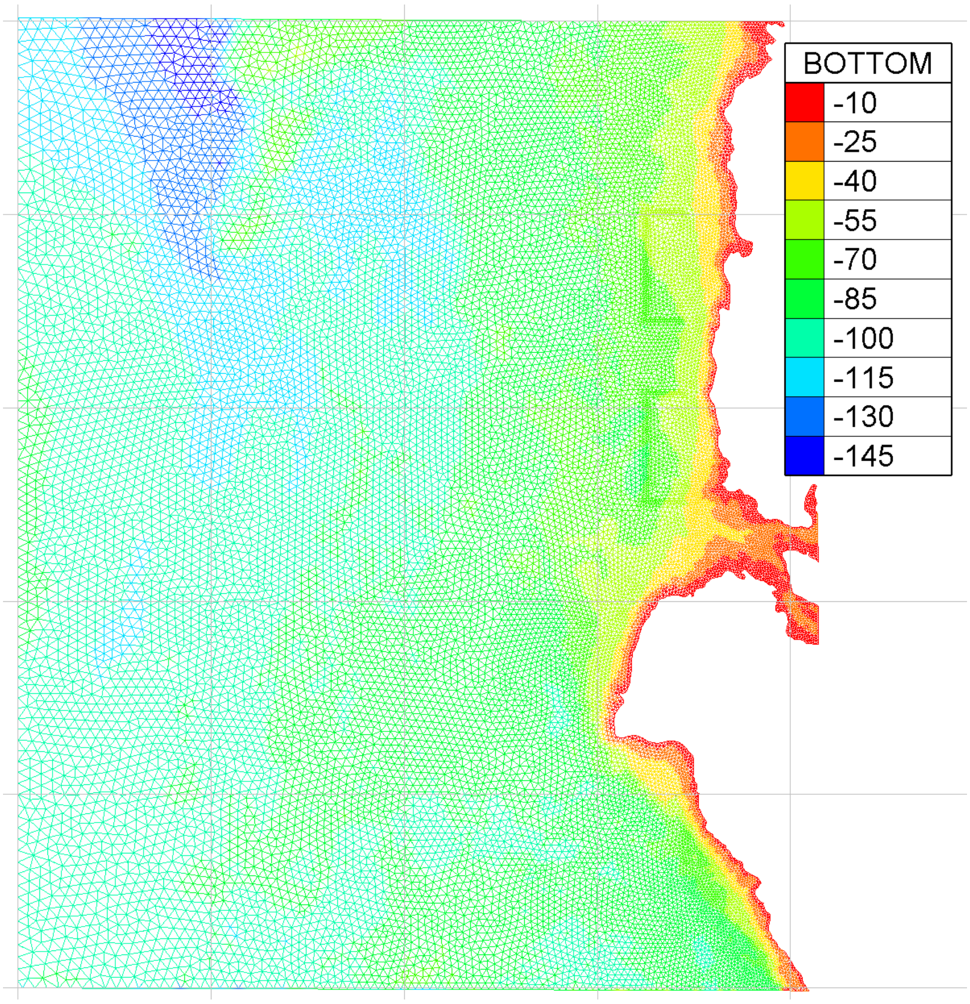


Figure 8: Mesh for the large domain

3.10 Step 9: Perform test runs

A number of test runs were completed to ensure that the model is acceptable. The first check undertaken was to assess that the time step is sufficiently short so that energy flows smoothly across the domain (if the time step is too long energy can skip nodes resulting in inaccurate energy propagation). This can be visually verified by looking at the significant wave height field at the end of the run. Figure 9 shows the significant wave height for Sea-state 4 of the representative sea states for the standard WEC array layout (5 rows, 100 metre spacing).

It can be seen that the wake behind the WECs in the array is continuous, which indicates that the time step is sufficiently short for the energy to propagate smoothly across the domain. Because the time step, computational frequencies, and device characteristics are the same for all of the model runs, it is sufficient to look at only one model run to verify this.

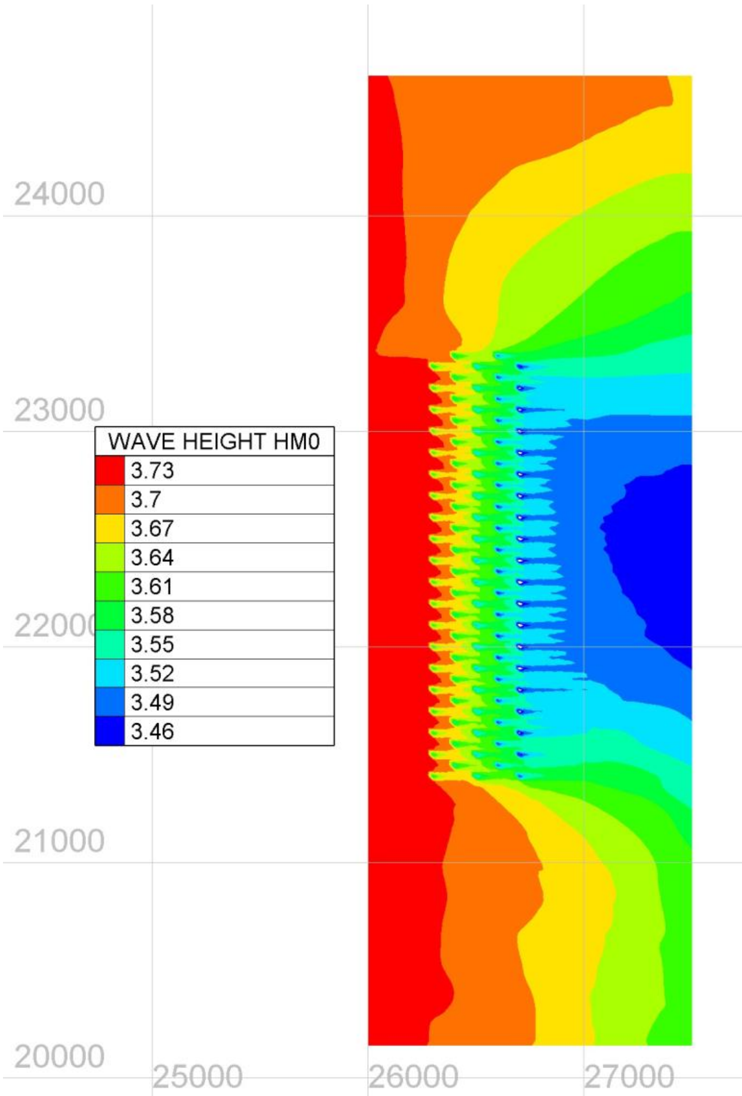


Figure 9: Significant wave height for sea state 4 with the standard WEC array.

The second check was to assess whether the model has reached a steady-state condition. This is tested by verifying that the significant wave height field does not vary significantly between time steps at the end of the run. This was assessed using Sea-state 4 of the representative sea states for the standard WEC array layout. It was found that the significant wave height is changing by no more than 0.24 millimetres throughout the whole domain. This is less than 0.01% of the significant wave height, which indicates that the system has essentially reached a steady state.

The final check was to confirm that the WEC source term strength does not extract more energy than available in any particular frequency component. This was done by inspecting the final wave spectra at the locations of the WEC devices for the standard array layout (5 rows, 100 metre spacing). Figure 10 shows the results for all 16 representative sea states. It can be seen that the wave energy densities at the WEC locations are diminished (as expected), but the energy content always remains positive.

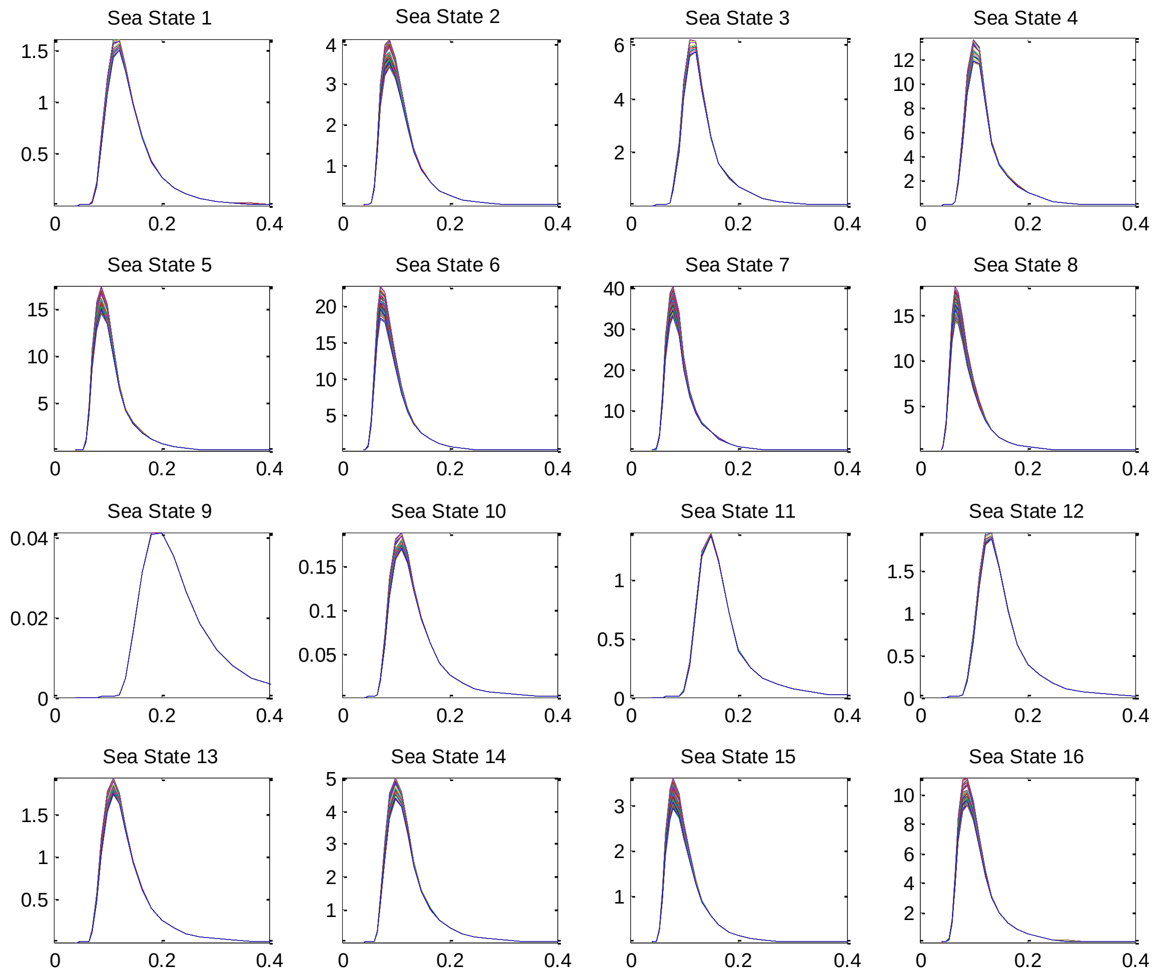


Figure 10: Final frequency spectra at the location of the WECs for all 16 representative sea states. These results are from the standard WEC array (5 rows, 100 metre spacing).

4 *Results and conclusions*

The SpecWEC methodology was applied to an array of 100 heaving buoys to assess the sensitivity of WEC array power capture to a number of different parameters. The results of this analysis are presented here. First, the results from the set of experiments using representative sea states are presented, beginning with the sensitivity of the power capture to array parameters such as layout and spacing, and then continuing with the power capture results for location parameter changes. Finally, the results of the set of experiments looking at changes in idealized sea state parameters are presented.

4.1 Representative sea states

4.1.1 Sensitivity to array parameters

The array power capture was calculated for all 16 representative sea states for three different array layouts consisting of 3 rows, 5 rows, and 10 rows.

Table 3: Array power capture results from array layout sensitivity test.

		3 rows		**5 rows**	10 rows	
Sea state	Weights	Power (MW)	Difference (%)	**Power (MW)**	Power (MW)	Difference (%)
1	0.049	1.28	+2.1	**1.26**	1.18	-5.7
2	0.096	6.31	+2.1	**6.18**	5.69	-8.0
3	0.071	4.61	+2.1	**4.52**	4.26	-5.7
4	0.076	14.16	+2.3	**13.84**	12.87	-6.9
5	0.147	24.24	+2.2	**23.71**	21.82	-7.9
6	0.029	38.96	+1.9	**38.24**	34.96	-8.5
7	0.018	64.25	+2.0	**62.98**	57.60	-8.5
8	0.015	32.60	+1.6	**32.08**	29.30	-8.6
9	0.041	0.00	+0.5	**0.00**	0.00	-1.0
10	0.037	0.19	+2.2	**0.19**	0.18	-6.5
11	0.063	0.35	+1.2	**0.34**	0.33	-2.8
12	0.186	1.03	+1.8	**1.02**	0.97	-4.5
13	0.117	1.84	+2.2	**1.80**	1.68	-6.3
14	0.036	5.99	+2.3	**5.85**	5.43	-7.2
15	0.015	6.04	+2.0	**5.92**	5.43	-8.3
16	0.008	17.14	+2.1	**16.78**	15.42	-8.1
SUM	**1.000**	**9.25**	**+2.0**	**9.06**	**8.35**	**-6.2**

The annual average power capture (calculated by applying the weightings to the sea states) is highest for the array layout with 3 rows and lowest for the array layout with 10 rows. This is because each row extracts some wave power, which is then not available to subsequent rows. Consequently, as would be expected the average power capture reduces as the number of rows increases.

Next, the array power capture was calculated for three different array spacings: 100 metres, 150 metres, and 200 metres. In this case, each of the arrays had 5 rows.

Table 4: Array power capture results for array spacing sensitivity test.

		100 m	150 m		200 m	
Sea state	Weights	**Power (MW)**	Power (MW)	Diifference (%)	Power (MW)	Difference (%)
1	0.049	**1.26**	1.26	+0.7	1.27	+1.0
2	0.096	**6.18**	6.20	+0.3	6.23	+0.9
3	0.071	**4.52**	4.55	+0.7	4.57	+1.0
4	0.076	**13.84**	13.92	+0.6	13.97	+1.0
5	0.147	**23.71**	23.80	+0.4	23.92	+0.9
6	0.029	**38.24**	38.23	+0.0	38.49	+0.7
7	0.018	**62.98**	63.03	+0.1	63.42	+0.7
8	0.015	**32.08**	32.00	+0.2	32.25	+0.5
9	0.041	**0.00**	0.00	+0.3	0.00	+0.4
10	0.037	**0.19**	0.19	+0.6	0.19	+1.0
11	0.063	**0.34**	0.35	+0.6	0.35	+0.9
12	0.186	**1.02**	1.02	+0.7	1.03	+1.0
13	0.117	**1.80**	1.81	+0.7	1.81	+1.0
14	0.036	**5.85**	5.89	+0.6	5.91	+1.0
15	0.015	**5.92**	5.93	+0.1	5.97	+0.8
16	0.008	**16.78**	16.83	+0.3	16.92	+0.8
SUM	**1.000**	**9.06**	**9.09**	**+0.5**	**9.14**	**+0.9**

The results show that as the array spacing increases, the array power capture increases as well. This is because larger inter-WEC spacings result in a smaller reduction in the incident wave energy density for subsequent rows. Consequently, as would be expected the average power capture increases as the inter-WEC spacing increases. This phenomenon has been described in previous studies (Borgarino et al., 2010).

4.1.2 Sensitivity to location parameters

The next sensitivity parameter was the physical location of the array. The arrays used for this test were the base design layout that consisted of 5 rows of devices with an inter-WEC spacing of 100 metres.

The power capture at the Baseline Location is higher than at Location 2 for all sixteen sea states. These differences must be due to the different bathymetry and coastline, as these are the only things that are different between the two cases. However, the boundary wave spectra were seen to be larger in the Baseline Location than Location 2 for each sea state, suggesting that the differences between the two were due at least in part to bathymetry outside of the small grid areas rather than entirely a change in array interactions due to the differing bathymetry within the small grid areas.

The array power capture was also calculated with and without the presence of a southward marine current with a magnitude of 0.5 m/s.

Table 5: Array power capture results from 2 different array locations.

		Location 1	Location 2	
Sea-state	Weights	**Power (MW)**	Power (MW)	Difference (%)
1	0.049	**1.26**	1.22	-2.6
2	0.096	**6.18**	5.86	-5.1
3	0.071	**4.52**	4.38	-3.1
4	0.076	**13.84**	13.23	-4.4
5	0.147	**23.71**	22.49	-5.2
6	0.029	**38.24**	35.74	-6.5
7	0.018	**62.98**	58.95	-6.4
8	0.015	**32.08**	29.74	-7.3
9	0.041	**0.00**	0.00	-0.1
10	0.037	**0.19**	0.18	-3.2
11	0.063	**0.34**	0.34	-1.3
12	0.186	**1.02**	1.00	-1.9
13	0.117	**1.80**	1.74	-3.1
14	0.036	**5.85**	5.62	-4.0
15	0.015	**5.92**	5.58	-5.9
16	0.008	**16.78**	15.88	-5.3
SUM	**1.000**	9.06	**8.59**	**-3.5**

Table 6: Array power capture results for the marine current sensitivity test.

		No current	0.5 m/s current	
Sea-state	Weights	**Power (MW)**	Power (MW)	Difference (%)
1	0.049	**1.26**	1.25	-0.1
2	0.096	**6.18**	6.17	-0.1
3	0.071	**4.52**	4.51	-0.1
4	0.076	**13.84**	13.82	-0.1
5	0.147	**23.71**	23.68	-0.1
6	0.029	**38.24**	38.19	-0.1
7	0.018	**62.98**	62.91	-0.1
8	0.015	**32.08**	32.05	-0.1
9	0.041	**0.00**	0.00	-0.1
10	0.037	**0.19**	0.19	-0.1
11	0.063	**0.34**	0.34	-0.1
12	0.186	**1.02**	1.01	-0.1
13	0.117	**1.80**	1.79	-0.1
14	0.036	**5.85**	5.85	-0.1
15	0.015	**5.92**	5.92	-0.1
16	0.008	**16.78**	16.76	-0.1
SUM	**1.000**	**9.06**	**9.05**	**-0.1**

The array power capture in the presence of the marine current was very slightly (approximately 0.1 %) less than the array power capture without the marine current. Thus, assuming that the WEC dynamics do not change due to the marine currents, then the influence of marine currents on the power capture of the WEC array tested here is minimal.

4.2 Sensitivity to sea state parameters

The array power capture and interaction factors were calculated for six idealized sea states over several ranges of sea state parameters.

Table 7: Array interaction factors for the idealized sea state parameter sensitivity study.

	SS1	SS2	SS3	SS4	SS5	SS6
Peak Direction						
Theta = 90	0.961	0.961	0.949	0.949	0.951	0.951
Theta = 100	0.960	0.960	0.949	0.949	0.951	0.951
Theta = 110	0.957	0.957	0.945	0.945	0.947	0.947
Theta = 120	0.953	0.953	0.939	0.939	0.940	0.940
Directional Spreading						
s = 99	0.965	0.965	0.955	0.955	0.956	0.956
s = 30	0.963	0.963	0.953	0.953	0.955	0.955
s = 15	0.961	0.961	0.949	0.949	0.951	0.951
s = 5	0.955	0.955	0.941	0.941	0.942	0.942
Bandwidth						
γ = 3.3	0.965	0.965	0.947	0.947	0.948	0.948
γ= 2.5	0.964	0.964	0.948	0.948	0.948	0.948
γ= 1.5	0.962	0.962	0.949	0.949	0.950	0.950
γ= 1.0	0.961	0.961	0.949	0.949	0.951	0.951
Energy Period						
dTe = -0.5	0.967	0.967	0.951	0.951	0.950	0.950
dTe = -0.25	0.964	0.964	0.950	0.950	0.950	0.950
dTe = 0	0.961	0.961	0.949	0.949	0.951	0.951
dTe = 0.25	0.959	0.959	0.949	0.949	0.952	0.952
dTe = 0.5	0.957	0.957	0.949	0.949	0.952	0.952
Significant wave height						
dHs = -0.5	0.961	0.961	0.949	0.949	0.951	0.951
dHs = -0.25	0.961	0.961	0.949	0.949	0.951	0.951
dHs = 0	0.961	0.961	0.949	0.949	0.951	0.951
dHs = 0.25	0.961	0.961	0.949	0.949	0.951	0.951
dHs = 0.5	0.961	0.961	0.949	0.949	0.951	0.951

Generally, the specified changes in the sea state parameters led to very small changes in the array interaction factor indicating that the estimated array interactions are not highly sensitive to the sea state parameters. Increasing the mean wave direction from 90 degrees (perpendicular to the wave array) to 120 degrees led to a decrease in the array interaction factor by at most 1.2 %.

Similarly, changes in the directional spreading did not result in differences in array interaction factor larger than 0.9 %. Variation of the bandwidth, energy period, and significant wave height resulted in changes in the array interaction factor of less than 0.6 %.

Table 8: Percentage change in array interaction factor due to changes in sea state parameters.

	SS1	SS2	SS3	SS4	SS5	SS6
Peak Direction						
Theta = 90						
Theta = 100	-0.1	-0.1	-0.0	-0.0	-0.0	-0.0
Theta = 110	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4
Theta = 120	-0.8	-0.8	-1.1	-1.1	-1.2	-1.2
Directional Spreading						
s = 99	+0.4	+0.4	+0.6	+0.6	+0.5	+0.5
s = 30	+0.2	+0.2	+0.4	+0.4	+0.4	+0.4
s = 15						
s = 5	-0.6	-0.6	-0.9	-0.9	-0.9	-0.9
Bandwidth						
γ= 3.3	+0.4	+0.4	-0.2	-0.2	-0.3	-0.3
γ= 2.5	+0.3	+0.3	-0.2	-0.2	-0.3	-0.3
γ= 1.5	+0.1	+0.1	-0.1	-0.1	-0.1	-0.1
γ= 1.0						
Energy Period						
dTe = -0.5	+0.6	+0.6	+0.1	+0.1	-0.1	-0.1
dTe = -0.25	+0.3	+0.3	+0.1	+0.1	-0.1	-0.1
dTe = 0						
dTe = 0.25	-0.2	-0.2	0.0	-0.0	+0.1	+0.1
dTe = 0.5	-0.5	-0.5	0.1	-0.1	+0.2	+0.2
Significant wave height						
dHs = -0.5	0.0	0.0	0.0	0.0	0.0	0.0
dHs = -0.25	0.0	0.0	0.0	0.0	0.0	0.0
dHs = 0						
dHs = 0.25	0.0	0.0	0.0	0.0	0.0	0.0
dHs = 0.5	0.0	0.0	0.0	0.0	0.0	0.0

4.3 Array design conclusions

The site case study presented here is an application of the SpecWEC methodology used to calculate the sensitivity of the array power capture to a variety of parameters. This set of results would allow the user to make informed decisions when designing an array of wave energy devices. The results suggest that, for these arrays of heaving buoy devices, average power capture is increased by having fewer rows in the array. Increasing the number of rows from 3 to 10 decreases the array power capture by about 10%. Similarly, it is better to have the largest spacing possible. However, this effect is not as pronounced as the number of rows, as increasing the spacing from 100 metres to 200 metres increases the array power capture by only 1%. This analysis also showed that variations of location could lead to a difference in array power capture of 5%. However, inclusion of marine current only had a very small effect on array power capture, and therefore does not seem to be that a significant factor. Of course, it should be noted that these results are only valid for a WEC with the characteristics specified. Modelling at another location or using a different WEC may produce a set of results that differ significantly from those produced by this case study. However, notwithstanding this caveat, for a similar type of WEC array at a similar location the results may be considered indicative and general conclusions on array design could be drawn. The sensitivity analysis carried out with idealized sea states also provided some interesting results. Despite variations in the bandwidth, peak direction, directional spreading, energy period, and significant wave height, only very small variations in the array interaction factor were found. This indicates that any errors resulting from inaccuracy in wave spectra measurements are likely to be negligible.

4.4 Applications and limitations of the methodology

The methodology presented here provides a framework for a user of the SpecWEC tool. It is designed to be as flexible as possible so that it can be used for a range of different applications. This tool can be used for estimates of array power capture for a large number of wave energy devices, as was demonstrated here in the site case study. It could also be used to look at the impact of the presence of an array of wave energy devices on the wave climate at any point in the model domain. The methodology is designed to give the user a list of the possible options that are available and to provide guidance on the selection of the most appropriate option. Notwithstanding this guidance, some of the choices that must be made for SpecWEC are primarily associated with the application of TOMAWAC and haven't been described in detail in the methodology. Guidance for these choices can be found in the TOMAWAC user manual and in some cases the TOMAWAC user forums. However, the case study presented here demonstrates that the SpecWEC tool can be used effectively by applying the methodology to assess the impact that different design choices may have on the WEC array power capture and thus support the design of a wave farm in general.

5 References

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